PB83-247585

Status of Dry SO2 Control Systems: Fall 1982

Radian Corp., Durham, NC

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Aug 83

U.S. Department of Commerce
National Technical Information Service
NTIS

PB83-247585

EPA-600/7-83-041
August 1983

STATUS OF DRY SO_2 CONTROL SYSTEMS:

FALL 1982

by

M. E. Kelly and M. A. Palazzolo
Radian Corporation
3024 Pickett Road
Durham, North Carolina 27705

EPA Contract No. 68-02-3171, Task 48

Project Officer: Theodore G. Brna
Industrial Environmental Research Laboratory
Utilities and Industrial Processes Division
Research Triangle Park, North Carolina 27711

Prepared for:

U. S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Office of Environmental Engineering and Technology
Washington, D. C. 20460

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/7-83-041

2.

3. RECIPIENT'S ACCESSION NO.
PB83 247585

4. TITLE AND SUBTITLE
Status of Dry SO2 Control Systems: Fall 1982

5. REPORT DATE
August 1983

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
M. E. Kelly and M. A. Palazzolo

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Radian Corporation
3024 Pickett Road
Durham, North Carolina 27705

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
68-02-3171, Task 48

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Research and Development
Industrial Environmental Research Laboratory
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED
Task Final; 3/82 - 2/83

14. SPONSORING AGENCY CODE
EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Theodore G. Brna, Mail Drop 61, 919/541-2683. Previous reports in this series are EPA-600/7-81-097, EPA-600/7-81-018, and EPA-600/7-80-030.

16. ABSTRACT
The report, updating the status of dry SO2 control systems for coal-fired utility and industrial boilers in the U.S. through the Fall of 1982, is based on current and recent research, research and development, and commercial activities. Systems addressed include: (1) spray dryer/fabric filter or electrostatic precipitator (ESP), (2) dry injection of alkali into flue gas followed by collection of particulates, (3) combustion of coal/alkali mixtures, and (4) electron-beam (E-beam) irradiation followed by particulate matter collection. Systems (1) and (2) provide both SO2 and particulate matter removal; (3) and (4) provide simultaneous SO2 and NOx control. Of the four systems, only spray drying has been commercialized; E-beam irradiation has not been tested beyond pilot scale. Dry injection of nahcolite into flue gas has been successfully demonstrated with a 22 MWe utility unit; unavailability of nahcolite hinders commercialization of this technology. Testing using low NOx burners for combustion of pulverized coal/limestone mixtures indicates SO2 captures of up to 70% in small scale tests; efforts to optimize SOx and NOx removal by this technology (limestone injection into a multistage burner--LIMB) are underway. Including four new utility systems sold since the last status report (Fall 1981) brings the total capacity served by dry flue gas desulfurization (FGD) to about 6200 MWe.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Fabrics	Pollution Control	13B	11E
Sulfur Dioxide	Electrostatic Precipitators	Stationary Sources	07B	
Coal		Dry SO2 Control	21D	13I
Combustion	Nitrogen Oxides	Fabric Filters	21B	
Boilers	Dust	Particulate	21A	11G
Utilities	Electron Beams	Electron-beam Irradiation		20H
Spray Drying	Irradiation		13H	18H

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS *(This Report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES
179

22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

THIS DOCUMENT HAS BEEN REPRODUCED FROM THE BEST COPY FURNISHED US BY THE SPONSORING AGENCY. ALTHOUGH IT IS RECOGNIZED THAT CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED IN THE INTEREST OF MAKING AVAILABLE AS MUCH INFORMATION AS POSSIBLE.

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ABSTRACT

This report is the fourth in a series of reports on the status of dry SO_2 control for utility and industrial boilers in the United States.* The information presented is based on a review of current and recently completed research, development, and commercial activities. Dry SO_2 control systems covered include: (1) spray dryers with a fabric filter or an electrostatic precipitator (ESP), (2) dry injection of alkaline material into flue gas accompanied by collection of product solids and fly ash in a fabric filter or an ESP, (3) combustion of coal/alkali fuel mixtures (LIMB), and (4) electron-beam (E-beam) irradiation. Spray drying and dry injection provide simultaneous SO_2 and particulate matter control while the combustion of coal/alkali fuel mixtures and the E-beam technology are designed to provide simultaneous SO_2 and NO_x control.

Spray drying continues to be the only one of the technologies commercially applied to utility and industrial boilers. Four new utility systems have been sold since the last survey, bringing the total utility spray drying flue gas desulfurization (FGD) capacity to about 6200 MWe. Also, two new industrial systems have recently been sold, making a total of eight commercial industrial boiler systems. Performance data have recently been published for several commercial spray drying systems, including a 440 MWe sodium-based system, two 100 MWe utility demonstration units, and two industrial systems applied to high sulfur coal-fired boilers. The full-scale systems that have come on-line since the last survey have generally met or exceeded SO_2 removal guarantees. Some of the systems, however, experienced atomization and solids build-up on the dryer walls during initial operation. (Reported design and operating experiences with full-scale systems are summarized in the report.)

Various research and development activities in all four technology areas are being funded by EPA, the Department of Energy (DOE), the Electric Power Research Institute (EPRI), and several process vendors.

---

*Previous reports are available from the National Technical Information Service (First Survey: EPA-600/7-80-030; Second Survey: EPA-600/7-81-018; and Third Survey: EPA-600/7-81-097.)

CONTENTS

Description Page

Abstract ii
Tables v
Figures viii
Acknowledgments xi

1.0 INTRODUCTION 1
  1.1 Report Organization 1
  1.2 Types of Dry SO$_2$ Control Systems 2
    1.2.1 Spray Drying 2
    1.2.2 Dry Injection 6
    1.2.3 Combustion of Coal/Alkali Fuel Mixtures 9
    1.2.4 Electron-beam Irradiation 12
  1.3 References 14

2.0 OVERVIEW 15
  2.1 Summary of New Developments 15
  2.2 Spray Dryer Systems 18
    2.2.1 Commercial Activities 18
    2.2.2 Research and Development Activities 36
  2.3 Dry Injection 54
  2.4 Combustion of Coal/Alkali Fuel Mixtures 59
  2.5 Electron-beam Irradiation 61
  2.6 References 61

3.0 CURRENT AND RECENTLY COMPLETED ACTIVITIES 63
  3.1 Babcock and Wilcox 63
  3.2 Combustion Engineering 65
  3.3 Cottrell Environmental Sciences/EPA 66
  3.4 DOE/Avco-Everett/EBARA and DOE/Research-Cottrell 71
  3.5 DOE/Grand Forks Energy Technology Center 72
  3.6 DOE/Pittsburgh Energy Technology Center 73
  3.7 Ecolaire Systems, Inc 80
  3.8 Electric Power Research Institute 82
  3.9 EPA - Alkali Injection Activities (LIMB) 91
  3.10 ETS, Inc 94
  3.11 Flakt, Inc 95
  3.12 General Electric Environmental Services, Inc 97
  3.13 Joy/Niro 102
  3.14 Mikropul Corporation/Koch Engineering Company, Inc 114
  3.15 Rockwell International 118
  3.15 Wheelabrator-Frye, Inc 120

4.0 TECHNICAL RESULTS FROM SPRAY DRYER SYSTEMS 125
  4.1 Reagent Preparation 126
  4.2 Atomization 128

4.3 Spray Dryer Design and Operation.......................... 132
4.4 Fabric Filter/ESP Design, Operation, and Performance....... 133
4.5 Solids Recycle... 136
4.6 Performance Data... 144
4.7 References... 150

5.0 DRY FGD WASTE DISPOSAL.. 152
5.1 Physical and Chemical Characteristics.................... 152
5.2 Current and Planned Disposal Methods for Commercial Units.. 163
5.3 References... 164

Appendix A - Conversion Factors.................................. 165

TABLES

Number — Page

1-1 Important Design and Operational Factors for Spray Drying FGD Systems.. 3

2-1 Summary of Utility Spray Drying Systems Sold to Date....... 19

2-2 Design Features Summary for Utility Commerical Spray Dryer Systems.. 21

2-3 Summary of Industrial Boiler Spray Drying Systems Sold to Date.. 23

2-4 Design Features Summary for Industrial Boiler Spray Drying Systems.. 24

2-5 Firms Offering a Commercial Spray Drying FGD System........ 27

2-6 Performance and Compliance Test Data for Spray Drying Systems.. 29

2-7 Process Conditions for Data Shown in Figure 2-1............ 31

2-8 Reported Utility Spray Dryer System Capital Costs.......... 34

2-9 Industrial Boiler Spray Drying Systems - Reported Capital Costs.. 35

2-10 Major Premises for EPRI Spray Dryer Costs................. 37

2-11 Bases for EPA Utility and Industrial Spray Dryer Costs..... 44

2-12 Lime Spray Dryer/Fabric Filter Process System Parameters for EPRI Costs.. 45

2-13 Spray Dryer/Fabric Filter Process Raw Materials and Utility Requirements for EPRI Costs............................. 46

2-14 Lime Spray Dryer/Fabric Filter - Utility System Capital Costs.. 47

2-15 Lime Spray Dryer/Fabric Filter - Utility System First Year Operating Costs.. 48

2-16 Lime Spray Dryer/Fabric Filter - Utility System 30-Year Levelized Revenue Requirements............................. 49

5-3 Description of Power Station Units and Operating Conditions During Sample Collection for Dry Scrubbing Systems Employing Lime Addition and Recycle........................ 157

5-4 Summary of Tests and Test Procedures...................... 158

5-5 Elemental Analysis of Spray Dryer Product from Baghouse During Recycle Demonstration Run in Joy/Niro Test Facility at Riverside Station.................................... 160

5-6 Elemental Analysis of Spray Dryer Product from Baghouse and Spray Dryer Hoppers (Mixed) when Pebble Lime was used as Reagent in Mikropul's FGD System at Strathmore Paper Company.. 161

FIGURES

Number		Page
1-1	Typical spray dryer/particulate collection flow diagram	4
1-2	Nahcolite dry injection flow diagram	7
1-3	Schematic diagram of distributed mixing burner	10
1-4	E-beam/ammonia process flow diagram	13
2-1	Comparison of overall SO_2 removal data for various lime-based spray dryer FGD systems	30
2-2	SO_2 removal data - Comanche pilot spray dryer tests	32
2-3	SO_2 removal data - Martin Drake pilot spray dryer	33
2-4	Lime spray dryer/fabric filter - utility system capital costs ($1980)	38
2-5	Lime spray dryer/fabric filter - utility system annual costs ($1980)	39
2-6	Lime spray dryer/fabric filter - utility system annualized costs ($1980)	40
2-7	Lime spray dryer/fabric filter - industrial system capital costs ($1980)	41
2-8	Lime spray dryer/fabric filter - industrial system annual costs ($1980)	42
2-9	Lime spray dryer/fabric filter - industrial system annualized costs ($1980)	43
2-10	Effect of inlet SO_2 concentration - Riverside data	55
2-11	Effect of nahcolite NSR on SO_2 removal	58
2-12	SO_2 capture in wall-fired furnaces	60
3-1	Relative SO_2 removal in spray dryer compared to fabric filter	68
3-2	Fabric filter SO_2 removal versus fabric filter pressure drop	69

3-3 PETC pilot-scale spray dryer test facility.................. 74

3-4 SO_2 removal with slaked lime (PETC)........................ 77

3-5 Effect of atomizer tip speed on SO_2 removal (1.0 reagent ratio).. 78

3-6 SO_2 removal with magnesium oxide........................... 79

3-7 Simplified process flow diagram for spray dryer pilot plant (rotary atomizer configuration)........................... 85

3-8 Schematic diagram of laboratory spray dryer system......... 87

3-9 Results of MgO recycle tests................................ 89

3-10 SO_2 capture in wall-fired furnaces........................ 93

3-11 Low sulfur coal parametric tests - Riverside............... 104

3-12 Low sulfur coal demonstration test results - Riverside..... 104

3-13 Spray dryer product moisture as a function of approach temperature - Riverside.................................. 106

3-14 Comparison of ABCOR pilot plant and Strathmore results..... 116

3-15 Coyote performance data at 65°F wet-bulb temperature (ΔT_{WB}).. 121

3-16 Coyote performance data at 50°F wet-bulb temperature (ΔT_{WB}).. 122

4-1 Atomizer types.. 129

4-2 Rockwell-designed atomizer for Coyote Station.............. 130

4-3 Spray dryer product moisture as a function of approach temperature - Riverside.................................. 134

4-4 Recycle addition configuration alternatives................ 138

4-5 SO_2 removal as a function of reagent ratio - Argonne system.. 140

4-6 Recycle and once-through results comparison................ 143

4-7 Comparison of overall SO_2 removal data for various lime-based spray dryer FGD systems........................... 146

4-8 SO_2 removal versus reagent ratio data - Comanche........... 148

4-9 SO_2 removal versus reagent ratio data - Martin Drake....... 149

5-1 Concentration of arsenic, barium, chromium, and selenium in extracts of dry scrubbing waste products before and after curing.. 162

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the ready cooperation of vendors and agency representatives in providing much of the information included in this survey. The thoughtful advice of Dr. T. G. Brna and Mr. James Kilgroe of EPA's Industrial Environmental Research Lab is also sincerely appreciated.

Section 1

INTRODUCTION

This report is the fourth in a series of reports on the status of dry flue gas desulfurization (FGD) processes in the United States for both utility and industrial applications.* Throughout this report, dry FGD will be defined as any process which involves contacting a sulfur-containing flue gas with an alkaline reagent and which results in a dry waste product for disposal. This includes (1) systems which use spray dryers for a contactor with subsequent baghouse or electrostatic precipitator (ESP) collection of waste products; (2) systems which involve dry injection of alkaline reagent into the flue gas with subsequent baghouse or ESP collection; (3) other varied dry systems which are primarily concepts that involve addition of alkaline reagent to a fuel prior to combustion; and (4) systems which involve reagent injection into the flue gas followed by electron-beam irradiation. This definition of dry systems excludes several dry adsorption or "acceptance" processes, such as the Shell/UOP copper oxide process and the Bergbau-Forschung adsorptive char process since the status of these processes has been documented in previous EPA reports. Fluidized bed combustion has also been excluded.

Also excluded was the regenerable Rockwell Aqueous Carbonate Process (ACP) which, although based on SO_2 removal with a spray dryer, does not fit the limitation of this study as being a "throwaway" system. However, the open loop, spray dryer contactor portion of the Rockwell process has been adapted for a "throwaway" system and, as such, has been included here.

1.1 REPORT ORGANIZATION

Section 2 presents an overview of the major types of dry FGD processes considered in this report and includes:

- A summary of new developments in the dry FGD area.
- A discussion of the recent commercial and developmental activities for each type of process (spray drying, dry injection, combustion of a coal/limestone fuel mixture, and electron-beam irradiation).

Section 3 presents descriptions of current and recently completed dry FGD research and development programs and commercial sales summaries. Section 4 provides a discussion of the technical results from full-scale dry FGD system operation and recent research and development programs. Finally, Section 5 provides information on the physical and chemical characteristics of dry FGD wastes, current and planned disposal methods for commercial units, and recently developed schemes for utilization of the waste solids.

---

*Previous report numbers EPA-600/7-80-030, EPA-600/7-81-018 and EPA-600/7-81-097. (Available through National Technical Information Service.)

1.2 TYPES OF DRY FGD SYSTEMS

This section provides a general process description for each of the four technologies being considered (i.e., spray drying, dry injection, combustion of coal/alkali fuel mixtures, and electron-beam irradiation). This background information is provided for the reader who may be unfamiliar with the technologies and is only intended to be a generalized description of the system.

Reagent ratio or sorbent stoichiometry for dry FGD systems, as used throughout this report, is defined as the moles of fresh reagent introduced to the system divided by the moles theoretically required for complete reaction with all the SO_2 entering the system. This definition results in a lower figure for the reagent ratio as compared to the conventional wet scrubbing definition, which is based on the moles of SO_2 removed by the system.

1.2.1 Spray Drying

Figure 1-1 is a schematic diagram of the spray drying FGD process. The gas containing fly ash and SO_2 enters the spray dryer and is contacted with a finely atomized alkaline slurry or solution. During the approximately 10-second residence time in the dryer, the flue gas is adiabatically humidified as the water in the slurry or solution is evaporated. Simultaneously, flue gas SO_2 reacts with the alkaline species to form solid sulfite and sulfate salts. The solids formed are dried to generally less than 1 percent free moisture. The flue gas, which has been humidified to within 20 to 50°F of its adiabatic saturation temperature, passes through the dryer and into a downstream high efficiency particulate matter control device. In some system designs a portion of the solids drop out of the dryer, but the bulk of the desulfurization products are collected with fly ash in a fabric filter or an ESP. The reaction between the alkaline material and flue gas SO_2 continues as the gas passes through the ductwork and the fabric filter or ESP. The most common reagent is lime, although sodium-based reagents are also used.

Table 1-1 lists the major design and operating factors for spray drying FGD. These considerations are discussed in more detail below.

Using a spray dryer for a flue gas contactor involves adiabatically humidifying the flue gas to within a specified number of degrees above saturation. With set conditions for inlet flue gas temperature and humidity and for a specified approach to saturation temperature, the amount of water which can be evaporated into the flue gas is set by energy balance considerations. Liquid-to-gas ratios are generally in the range of 0.2 to 0.3 gal./kcf.* The amount of reagent added (reagent ratio) is varied by raising or lowering the concentration of a solution or weight percent solids

---

*To conform with general engineering practice, English Engineering rather than metric units are normally used in this report. Appendix A provides conversion factors from English Engineering to International System (SI) units.

TABLE 1-1. IMPORTANT DESIGN AND OPERATIONAL FACTORS FOR SPRAY DRYING FGD SYSTEMS

Operational Factors

- Approach to saturation at dryer outlet
- Reagent ratio (amount of reagent added per unit of inlet SO_2)
- Inlet SO_2 concentration
- Temperature drop over the spray dryer
- Fly ash alkalinity
- Gas residence time

Design Factors

- Spray dryer design (gas distribution, gas exit configuration)
- Atomizer type
- Slaker type
- Use of solids recycle
- Use of flue gas bypass

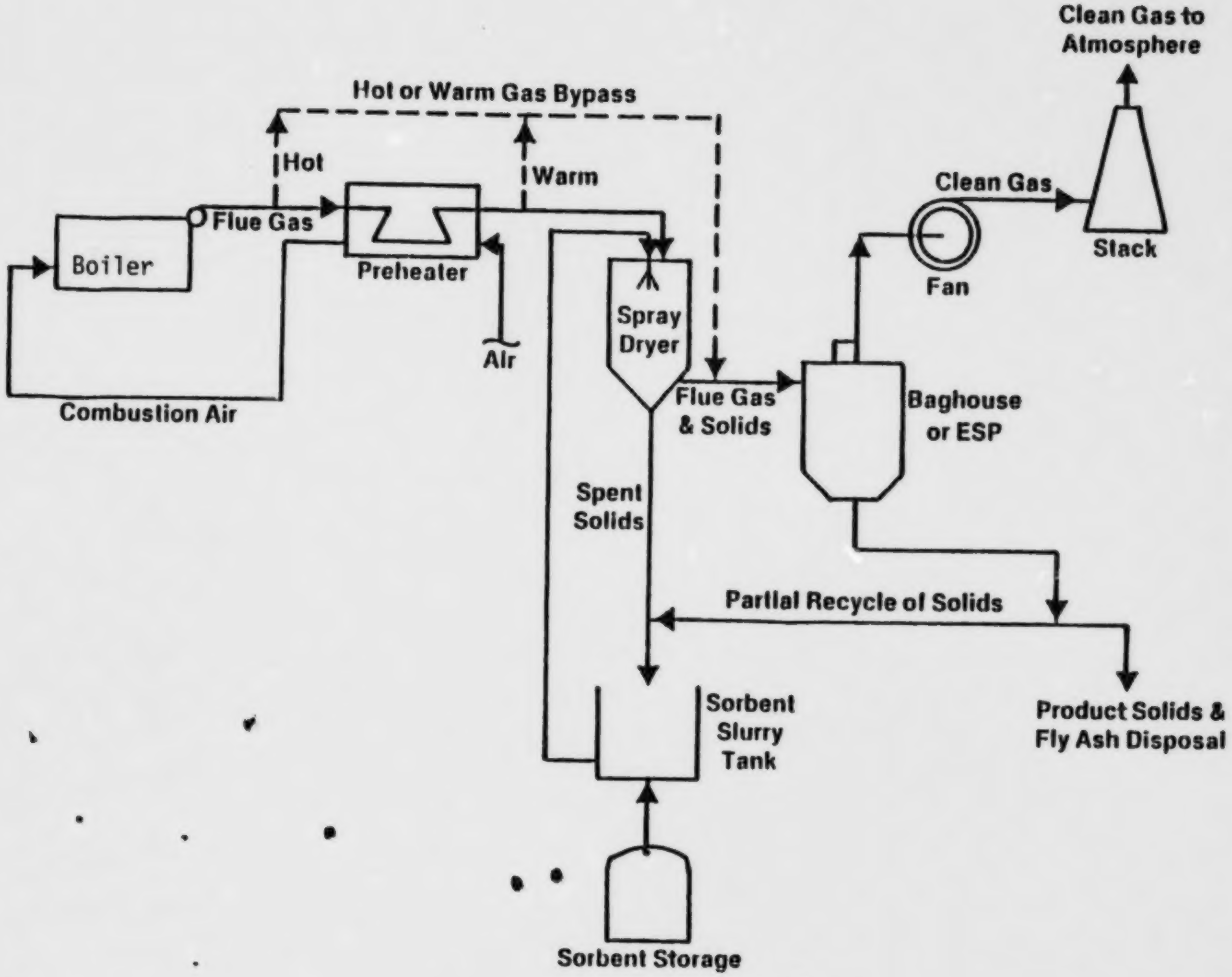

Clean Gas to
Atmosphere
Hot or Warm Gas Bypass
Hot
Warm
Clean Gas
Flue Gas
Boiler
Preheater
Stack
Fan
Air
Spray
Dryer
Combustion Air
Flue Gas
& Solids
Baghouse
or ESP
Spent
Solids
Partial Recycle of Solids
Sorbent
Slurry
Tank
Product Solids &
Fly Ash Disposal
Sorbent Storage

Figure 1-1. Typical spray dryer/particulate collection flow diagram.

of a slurry containing this set amount of water. While holding other parameters such as temperature constant, the obvious way to increase SO_2 removal is to increase the amount of reagent added. However, as the reagent ratio is increased to raise the level of SO_2 removal, two limiting factors are approached:

- Reagent utilization decreases, raising reagent and disposal costs.
- An upper limit is reached for the solubility of the reagent in the solution, or for the weight percent of solids in the slurry.

There are at least two methods of circumventing these limitations. One method is to initiate solids recycle, using the solids that have either dropped out in the spray dryer or collected in the particulate emission control device. Recycle has the advantage of increasing reagent utilization, and it can increase the opportunity for utilization of any alkalinity in the fly ash.

The second method of avoiding the above limitations on SO_2 removal is to operate the spray dryer at a lower outlet temperature; that is, a closer approach to saturation. Operating the spray dryer at a closer approach to saturation has the effect of increasing both the residence time of the liquid droplets and the residual moisture level in the dried solids. As the approach to saturation is narrowed, SO_2 removal rates and reagent utilization generally increase dramatically.

The approach to saturation at the spray dryer outlet is set by either the requirement for a margin of safety to avoid condensation in downstream equipment or restrictions on stack temperature. The spray dryer outlet can be operated at temperatures lower than these restrictions would otherwise allow if some warm or hot gas is bypassed around the spray dryer and used to reheat the dryer outlet gas. Warm gas (from downstream of the boiler air heater) can be used at no energy penalty, but the amount of untreated gas involved in reheating begins to limit overall SO_2 removal efficiencies. Significantly less hot gas (upstream of the air heater) is required for heating, but an energy penalty associated with the decrease in energy available for air preheat comes with using this higher temperature gas. Figure 1-1 illustrates these two reheat options.

Differences in spray dryer operation include gas residence time and the approach to saturation at the dryer outlet. Gas residence times range from 7 to 12 seconds in most commercial system designs, with the majority operating in the 10- to 12-second range. Many commercial system designs call for a relatively close approach to saturation at the dryer outlet of 18 to 25°F. These close approaches are common in applications where SO_2 removal efficiency requirements approach 85 to 90 percent, but may also be used to decrease reagent use in lower removal efficiency applications. Some designs, however, are based on a wider approach to saturation of 30 to 50°F.

Atomization techniques vary with regard to the use of rotary or nozzle atomizers, atomizer wheel speed in rotary atomizers, atomizing fluid (air or steam) for nozzles, and the number of atomizers per dryer. Rotary atomizers are commonly used on a single atomizer per dryer basis, but two commercial utility systems will rely on three atomizers per dryer.

The method used to slake the lime also varies between commercial system designs. Ball mill, paste, and detention slakers are all used, although ball mill and paste slakers are more common. Each method is perceived to have certain advantages. Ball mill slakers generally produce a more finely ground and possibly more reactive slurry, and unlike paste slakers, there is no grit removal stream to dispose of. Paste slakers, on the other hand, have lower capital costs and lower power requirements. Also, they generally produce a less abrasive slurry than do ball mills, which could reduce the potential for wear and maintenance of system pumps and piping.

Fabric filters have been chosen over ESP's in most of the commercial spray drying applications to date. Fabric filters may have an advantage over ESPs in that unreacted alkalinity in the solids and fly ash collected on the fabric surface can react with remaining SO_2 in the flue gas as the gas passes through the fabric filter. Some process developers have reported that SO_2 removal across the fabric filter can account for at least 10 percent of the total system SO_2 removal. In some applications, however, an ESP might be more desirable than a fabric filter. The factors that are important in making the choice between ESP's and fabric filters include (1):

- Use of solids recycle (increases dust loading to ESP, thus increasing ESP size and cost).

- Fly ash resistivity (high ash resistivity often requires larger, more expensive ESP's).

- Pressure drop considerations (an ESP will result in lower pressure drop costs than a fabric filter).

Fabric filter designs for spray dryer FGD systems vary primarily with regard to bag fabric, cleaning frequency, and cleaning cycle. There are also more subtle variations, too numerous to mention here, between the well-established fabric filter design practices of the different vendors. Teflon-coated fiberglass bags have been selected for many systems, although acrylic bags are also considered as alternatives.

1.2.2 Dry Injection

Dry injection schemes generally involve pneumatically introducing a dry, powdery alkaline material into a flue gas stream with subsequent particulate collection. A generalized flow diagram of this process is shown in Figure 1-2. The injection point has been varied from the boiler furnace area all the way to the flue gas entrance to an ESP or bag collector. Most dry

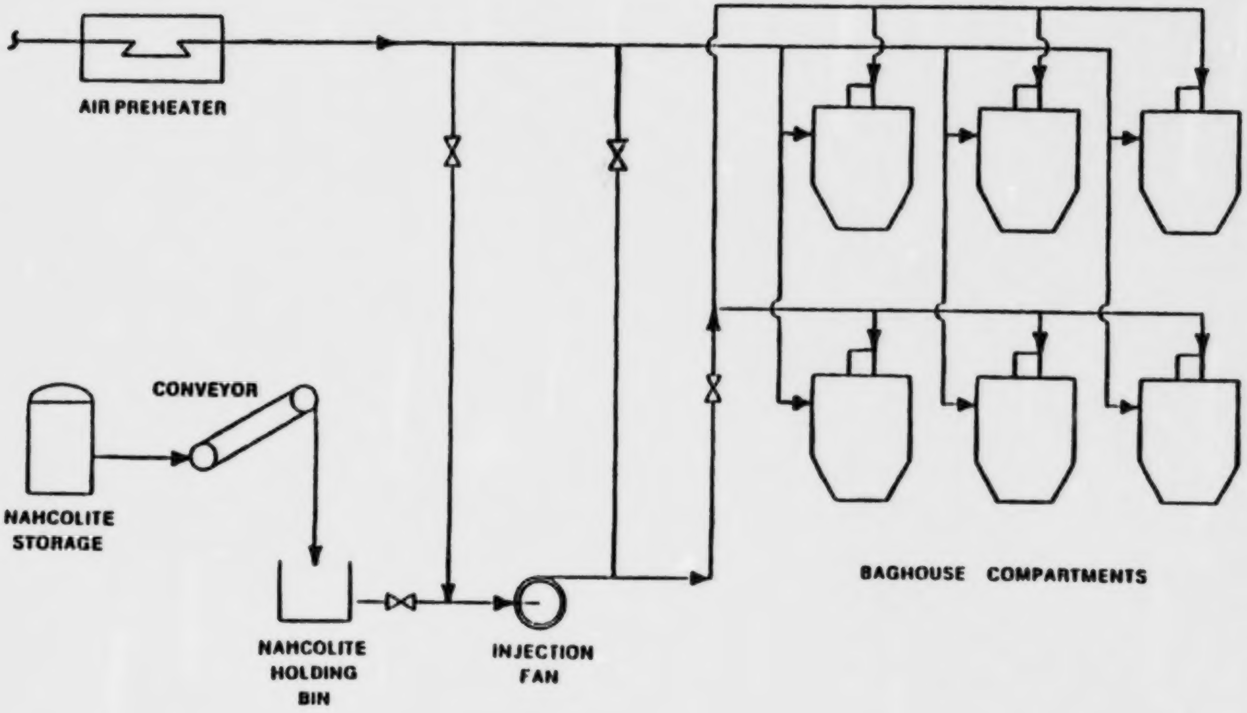

AIR PREHEATER
CONVEYOR
NAHCOLITE STORAGE
NAHCOLITE HOLDING BIN
INJECTION FAN
BAGHOUSE COMPARTMENTS

Figure 1-2. Nahcolite dry injection flow diagram.

1-2

injection schemes use a sodium-based sorbent. Lime has been tested but has not been demonstrated with much success. Many dry injection programs have used nahcolite as a sorbent. Nahcolite is a naturally occurring mineral, usually associated with western oil shale reserves, and is about 80 percent sodium bicarbonate. Sodium bicarbonate appears to be more reactive than sodium carbonate, because it loses both two moles of CO_2 and one of water in reaction, while sodium carbonate loses only one mole of CO_2 in reaction with SO_2. The following overall reactions illustrate this point:

$$2NaHCO_3 + SO_2 \longrightarrow Na_2SO_3 + H_2O + 2CO_2 \qquad (1\text{-}1)$$

$$Na_2CO_3 + SO_2 \longrightarrow Na_2SO_3 + CO_2 \qquad (1\text{-}2)$$

Since bicarbonate loses three moles for every mole of SO_2 removal, bicarbonate particles tend to have larger pore volumes and are apparently less susceptible to blinding on reaction than are sodium carbonate particles. Unfortunately, the availability of raw nahcolite in commercial quantities in the near future is questionable due to the substantial investment necessary before commercial-scale mining can begin. However, one firm, the Multi Mineral Corporation, has obtained data for an environmental impact study. Multi Mineral estimates that annual production of about 1 million tons of nahcolite would be achievable in about 4 years (2). The potentially favorable economics of dry injection are based to some extent on the use of inexpensive sorbents, and the use of commercially refined sodium bicarbonate is likely to be prohibitively expensive. Recent research has been aimed at studying the use of raw and upgraded trona ore. The mineral trona contains one mole of sodium carbonate, one mole of sodium bicarbonate, and two waters of hydration ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). Upgraded trona from the Owens Lake, California area, has the potential for providing a good compromise between reactivity, cost, and availability for use as a sorbent in the dry injection process (2).

Both baghouse and ESP collection devices have been tested with dry injection processes. However, the effect of the reaction between unspent sorbent on collecting bag surfaces and SO_2 remaining in the flue gas seems overwhelmingly to favor the bag collector. Since a significant portion of the SO_2 removal reaction appears to take place on the bag surface, various methods of feeding have been tested:

- Continuous. After the bag is cleaned, sorbent entrained in the flue gas is continuously supplied to the bag surface from injection points located upstream of the baghouse.

- Batch. After the bag is cleaned, all sorbent is added to the bag as a precoat before flue gas flow is resumed.

- Semi-batch. This feeding method is a combination of the continuous and batch methods described above. After bag cleaning some sorbent is precoated onto the bags and the remainder is added continuously at an upstream injection point.

Sorbent stoichiometry, sorbent particle size, location of injection point, temperature at the point of injection, baghouse air-to-cloth ratio, and bag cleaning frequency have also been varied in dry injection test programs to determine their impact on SO_2 removal.

1.2.3 Combustion of Coal/Limestone Fuel Mixtures

Research on combustion of a coal/limestone fuel mixture has primarily taken two forms:

- Combustion of a coal/limestone pellet in an industrial spreader-stoker boiler.

- Combustion of a pulverized coal/limestone mixture in a low-NO_x burner system.

Recently, most of the effort has been directed toward the second concept, which is often referred to as the LIMB process (limestone injection in a multi-stage burner). The basic concept of the LIMB is injection of pulverized coal and limestone into the boiler combustion chamber where the limestone calcines to lime and then reacts with SO_2 to form calcium sulfite or calcium sulfate. These reacted solid sulfur compounds and fly ash are subsequently collected in a particulate matter emission control device.

Early U. S. attempts at SO_2 emission control by injecting a dry sorbent into the boiler were not considered to be successful (3). This work involved high sulfur bituminous coals, limestone or lime, and high turbulence burners. Major problems included low SO_2 removal efficiencies, low reagent utilization, fouling of heat exchanger surfaces, pluggage of convective passages, and loss of precipitator efficiency.

The major factor causing low limestone utilization and poor SO_2 removal during these studies was the high flame temperatures associated with the burner and fuel types tested. At the high flame temperatures, the injected limestone particles became sintered, limiting the SO_2 reaction. In addition, at flame temperatures above 2200°F, previously formed $CaSO_4$ becomes thermally unstable and is reconverted to SO_2.

More recent limestone injection tests with low-NO_x distributed mixing burners (DMB) have been more successful. As shown in Figure 1-3, the mixing of fuel and combustion air in the DMB is delayed to lower the flame temperature and produce reducing gases that convert fuel nitrogen to N_2. The low-NO_x burner provides an improved time/temperature profile for limestone injection compared to conventional burners because (1) the lower temperature reduces the likelihood of limestone sintering or deadburning and

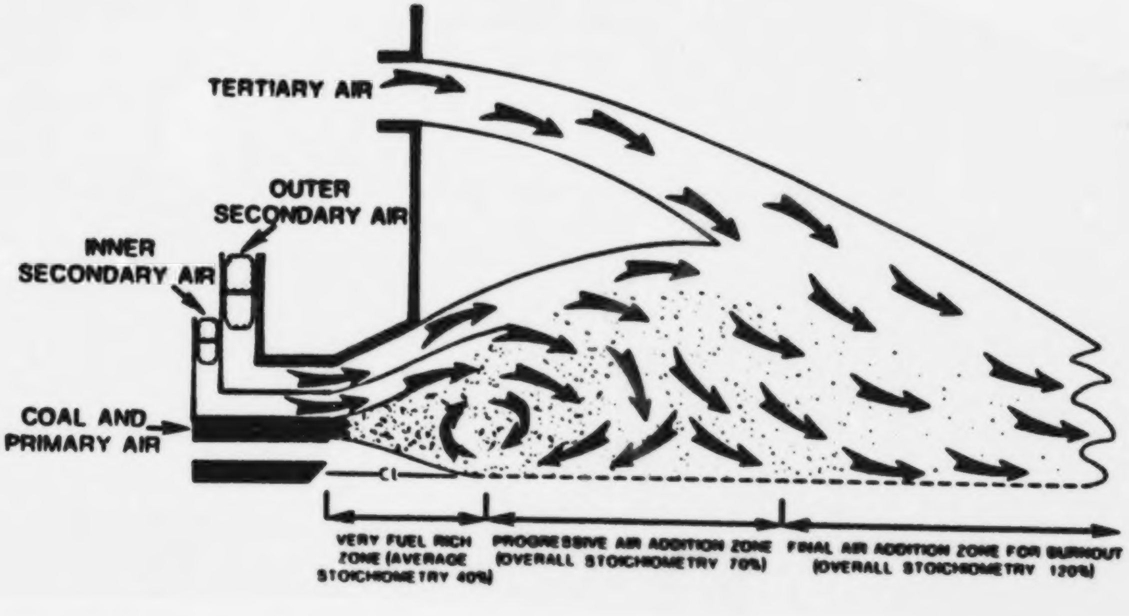

TERTIARY AIR
OUTER SECONDARY AIR
INNER SECONDARY AIR
COAL AND PRIMARY AIR
℄
VERY FUEL RICH ZONE (AVERAGE STOICHIOMETRY 40%)
PROGRESSIVE AIR ADDITION ZONE (OVERALL STOICHIOMETRY 70%)
FINAL AIR ADDITION ZONE FOR BURNOUT (OVERALL STOICHIOMETRY 120%)

Figure 1-3. Schematic diagram of distributed mixing burner.

(2) the longer residence time provides more time for the sulfation reaction to occur.

Design and operating parameters important to the LIMB process include coal properties, reagent ratio, gas SO_2 concentrations, location of reagent injection, burner and boiler design, and post-combustion flue gas treatment systems.

Coal properties that affect SO_2 capture efficiencies by LIMB include the coal moisture content and the fuel composition. These properties affect the heat release rate during combustion and, thereby, the peak temperatures in the burner flame zone and furnace volume. Other important coal properties are the coal alkalinity and sulfur content, which can affect the amount of sulfur captured by the coal ash and the SO_2 concentration in the flue gas.

Removal efficiencies have been found to be dependent on the calcium-to-sulfur ratio (Ca/S) of limestone to coal and the square root of the SO_2 concentration ($\sqrt{SO_2}$) in the fuel combustion products (4). Higher SO_2 removals can be achieved with higher Ca/S ratios and at higher SO_2 concentrations. The location of limestone injection has been found to have an important effect on SO_2 removal. The effects of injecting limestone with the coal, the primary air, the tertiary air, or a third source of combustion air outside the burner area continue to be evaluated. Results to date indicate that the optimum location will vary, depending on the burner design, the method of operation, and the method of limestone injection. In tests where more than 50 percent of the combustion air was primary air, limestone injection outside of the burner zone provided the highest SO_2 removals (5). However, in other tests injection with the primary air produced the best results (4). In the latter tests, temperatures outside of the burner zone were too low to achieve limestone calcination.

Furnace design is also important in that it affects the volumetric heat release rate and heat flux within the furnace volume. Lower temperatures favor the control of both SO_2 and NO_x emissions.

Fouling and plugging problems are a function of the furnace and boiler design, the coal properties, and the sorbent properties. For new boilers designed specifically for LIMB application, fouling and plugging problems can probably be avoided. In some existing designs, furnace volume, furnace heat transfer surfaces, and boiler tube spacing--when taken in conjunction with coal and sorbent types--may limit the application of LIMB.

The use of various flue gas treatment schemes for LIMB applications has not yet been evaluated. Possible schemes include the use of ESP's, fabric filters, and scrubbers for particulate control. EPA plans to evaluate these methods and the use of a spray dryer for auxiliary SO_2 control. Selection of the appropriate particulate collection device will depend upon the particle properties, the desired control level, and the costs of control using various devices. Retrofit applications may require modification of or addition to the existing particulate control equipment to achieve a satisfactory level of control.

Data from LIMB experiments suggest that SO_2 collection efficiencies of 50 to 70 percent can be attained at Ca/S ratios of 2 to 3 in modified systems. Higher removal efficiencies may be attainable with newly designed boilers. A substantial amount of further development work will be required before the commercial feasibility of LIMB is demonstrated.

1.2.4 Electron-beam Irradiation Systems

Electron-beam (E-beam) processes involve the irradiation of flue gas containing a reactant, such as ammonia or lime. The process removes both SO_2 and NO_x from the flue gas and results in a dry waste product.

A schematic diagram of the E-beam/ammonia process is shown in Figure 1-4. In this process, incoming flue gas is cooled and humidified in a quench tower. The resulting gas moisture content is about 10 percent. Ammonia is injected into the cooled gas and the gas is passed through an E-beam reactor. In the reactor, oxygen and water are ionized to form the radicals [HO], [O] and [HO_2] by the application of electrons at a dose of 1 to 3 Mrads (1 Mrad is equivalent to 10 joules/g of flue gas). These radicals react with SO_2 and NO_x to form sulfuric acid (H_2SO_4) and nitric acid (HNO_3). The acids are neutralized by ammonia and water in the flue gas to form solid ammonium sulfate (NH_4SO_4) and ammonium sulfate nitrate ($(NH_4)_2\ SO_4 \cdot 2\ NH_4NO_3$). The reaction time for formation of the sulfate and nitrate salts is less than one second.

Product solids are collected in a hopper below the E-beam reactor or in a downstream particulate collector.

In another version of the E-beam process, the water quench tower is replaced with a lime-based spray dryer. Reactions in the E-beam reactor occur in the same manner as in the ammonia process except that the products formed are calcium salts ($CaSO_4$, $Ca(NO_3)_2$ and $CaSO_3$) instead of ammonium salts.

The lime spray dryer/E-beam and ammonia/E-beam processes have not yet been tested on a real coal-fired flue gas. The lime process has been tested on a bench-scale and the ammonia process has been tested on a pilot-scale at a steel sintering plant. The bench- and pilot-scale studies have shown that variables important to performance include gas moisture content, gas temperature, oxygen content, reagent ratio, and electron dosage.

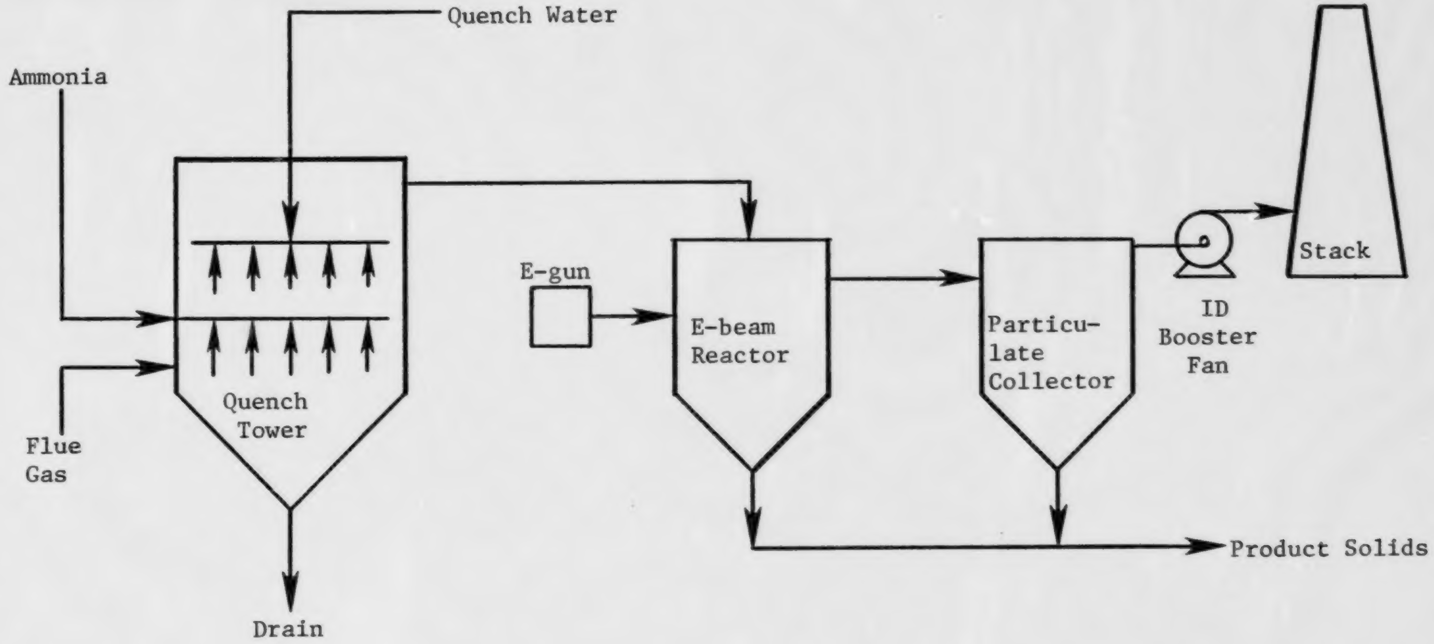

Quench Water
Ammonia
Flue Gas
Quench Tower
Drain
E-gun
E-beam Reactor
Particulate Collector
ID Booster Fan
Stack
Product Solids

Figure 1-4. E-beam/ammonia process flow diagram.

REFERENCES

1. Meyler, J. A. Joy Industrial Equipment Co. Western Precipitation Division. Telephone conversation with M. E. Kelly, Radian Corporation, March 9, 1982.

2. Furlong, Dale A., T. G. Brna, and R. L. Ostop. "SO_2 Removal Using Dry Sodium Compounds." (Presented at the 89th National AIChE Meeting. Portland, Oregon. August 17-20, 1980.)

3. Gartrell, F. E. (TVA). Full Scale Desulfurization of Stack Gas by Dry Limestone Injection, Volume I. EPA-650/2-73-019a (NTIS PB 228-447/AS), U. S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, NC, August 1973.

4. Drehmel, D. C. U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, NC. Conversation with J. D. Kilgroe, April 16, 1982.

5. Flament, G. The Simultaneous Reduction of NO_x and SO_2 in Coal Flames by Direct Injection of Sorbents in a Staged Mixing Burner. Document No. G/19a/10, International Flame Research Foundation, Estel-Hoogovens, The Netherlands, September 1980.

SECTION 2

OVERVIEW

Interest in dry SO_2 control has remained strong during the year and a half since the last survey was published. Four new utility and two new industrial spray drying systems have been sold, and operating experience with a number of full-scale commercial systems has been reported. Information has been published on the use of spray drying for high sulfur coal applications, an area that is the focus of several of the current or recently completed pilot- and demonstration-scale test programs. Also, new data have been reported on both dry injection and LIMB technologies, and the Department of Energy (DOE) has established a program for development of electron-beam (E-beam) irradiation techniques for combined SO_2 and NO_x removal.

Section 2.1 provides a summary of new developments in dry SO_2 control for utility and industrial boilers. Sections 2.2 through 2.5 provide more detail on the recent activities involving each of the technologies covered by the survey: spray drying, dry injection, LIMB, and E-beam irradiation.

Work is also continuing in the waste disposal area. Studies are focused on characterizing solid waste properties as a function of coal type and FGD process conditions and on defining suitable waste disposal or utilization methods. Waste disposal-related activities are discussed in Section 5 of this report.

2.1 SUMMARY OF NEW DEVELOPMENTS

Spray drying continued to be the only dry SO_2 control process commercially applied to utility or industrial boilers. Four new utility systems have been awarded since the last survey, bringing the total utility spray drying FGD capacity to about 6200 MWe. This total includes a 110 MWe system at Northern States Power Co.'s Riverside Station and a 100 MWe system at Pacific Power and Light Co.'s Jim Bridger Station. Both of these systems have been retrofit to existing boilers and are currently operated by the respective system vendors as demonstration units. The utilities may, however, commercially operate the systems after the demonstration programs are complete.

Two new industrial awards have been made since late 1981, making a total of eight spray drying systems applied to industrial boilers.

Performance and compliance test results were recently reported for two utility systems (Montana-Dakota Utilities' Coyote Station and the Jim Bridger system) and three industrial systems (Argonne, Strathmore, and Container Corporation). Data from tests at the Riverside system and results of pilot-scale testing funded by EPA and DOE have also been published. In general, the performance test results have shown that the commercial systems have met or exceeded SO_2 and particulate matter removal guarantees. Recently published data have also indicated that 90 percent or greater SO_2 removal is achievable for high sulfur applications (3 to 3.5 percent sulfur coal with a corresponding inlet SO_2 concentration of 2000 to 2500 ppmv). More detail on these performance and pilot tests is given in Section 2.2.

Several commercial spray drying systems are currently in the initial start-up stages or entering the final phase of construction. Four utility and two industrial systems should be in start-up or performance test stages by the end of 1982. Three more utility and two more industrial systems are scheduled to be operating by the end of 1983.

Vendors report having several utility system bids under evaluation. The market outlook for industrial boiler spray drying systems has been clouded by delays in the proposal of new source performance standards (NSPS). However, market opportunities may still be generated in situations where SO_2 or combined SO_2 and particulate control is required by state or local regulations or for prevention of significant deterioration (PSD) permits.

A major development in spray drying has been the recent successful application of the technology to higher sulfur coal-fired boilers. Data have been made available from two full-scale industrial systems (Argonne and Strathmore), the Riverside demonstration tests, EPA-funded tests at Martin Drake, and DOE-funded tests at the Pittsburgh Energy Technology Center. All of these results were obtained at flue gas inlet SO_2 concentrations of greater than 2000 ppmv. The data generally indicate that, at a relatively close approach to saturation of 18 to 20°F, reagent ratios of at least 1.35 are required to achieve 90 percent SO_2 removal.

Operating experience with full-scale commercial systems has been reported as relatively trouble-free, although some systems experienced problems with atomization and build-up of wet solids on the dryer walls during initial operation. (Operating and design problems encountered with full-scale systems in the past year are discussed in Section 4 of this report.)

Spray drying demonstration- and pilot-scale testing and research continues to focus on refinement of spray dryer design and operation, comparison of rotary and nozzle atomizers, and investigation of the mechanisms and benefits of solids recycle for lime systems. Other areas of spray drying research and development include optimization of lime slaking and investigation of alternate reagents such as limestone, dolomitic lime, adipic acid-enhanced lime and limestone, and MgO.

Dry injection technology has not yet been commercially applied to utility or industrial boilers. However, EPRI has recently published data from demonstration-scale tests of the process. EPRI's tests were conducted on a 22 MWe system at Public Service Company of Colorado's Cameo Station.

Sulfur dioxide removals of 75 to 83 percent were demonstrated with nahcolite at a reagent ratio of 1.0 mole Na_2O per mole of inlet SO_2 and an inlet SO_2 concentration of about 450 ppmv.

The commercial application of dry injection continues to be constrained by uncertainties regarding reagent cost and availability and waste disposal concerns related to the undesirable solubility and leachability properties of the sodium-based waste products. Nahcolite, which is generally found associated with oil shale deposits, is not currently mined in commercial quantities. Multi Mineral Corporation of Grand Junction, Colorado is the only firm that has publically announced intentions to develop a commercial nahcolite mining operation.

The LIMB process is still in the relatively early stages of development. EPA plans to continue evaluating the technology on laboratory burners as well as commercial boilers of various designs. At least two U.S. boiler manufacturers are reported to be conducting pilot-scale tests of the LIMB concept. One of the companies, Babcock and Wilcox (B&W), has investigated furnace limestone injection followed by spray drying. Additional testing of this concept is to be performed by B&W under DOE sponsorship. Furnace limestone injection has also been investigated at DOE's GFETC.

Considerable development work remains before the LIMB concept or other technologies involving furnace limestone injection are commercially applicable. However, there are a number of factors providing impetus for continued development of such technologies, including:

- desirability of combined SO_2/NO_x control,
- incentives for development of lower cost SO_2 control techniques, and
- the potential for acid rain legislation requiring retrofit SO_2 control.

A key factor in determining the applicability of LIMB technologies for specific boilers will be the minimization of potential adverse effects on boiler operation (e.g., fouling or slagging caused by firing a mixture of coal and limestone.) EPA has recently provided funding for a program designed to investigate the effects of LIMB on boiler and downstream pollution control equipment design and operation.

The electron-beam irradiation process is also aimed at achieving simultaneous SO_2 and NO_x control. The primary activities being funded by DOE in this area are pilot-scale tests of two process concepts and kinetic studies. DOE sees the potential for increased emphasis on stationary source NO_x control as providing a major incentive for developing a technology with the potential for achieving combined SO_2 and NO_x control in the 70 to 90 percent removal range.

2.2 SPRAY DRYER SYSTEMS

The following sections summarize recent commercial and R&D activities in the spray drying area. The commercial sales made to date, experience with full-scale systems, performance or compliance test results, and cost data are highlighted in Section 2.2.1. Current or recently completed spray drying R&D programs and major results from these programs are discussed in Section 2.2.2. More detail on these commercial and R&D activities can be found in Sections 3 and 4 of this report.

2.2.1 Commercial Activities

Tables 2-1 through 2-4 present the key features of the utility and industrial boiler spray drying FGD systems sold to date. Utility systems are covered in Tables 2-1 and 2-2 and Tables 2-3 and 2-4 provide similar information for the industrial boiler systems.

Utility Systems

Table 2-1 shows the 17 utility systems sold to date. The applications range in size from 44 to 860 MWe (gross electrical output) and total about 6200 MWe in FGD system capacity. Two retrofit systems, at Northern States Power Co.'s Riverside Station and Pacific Power and Light Co.'s Jim Bridger Station, are currently being operated as demonstration systems by their respective vendors. Joy/Niro operated the Riverside system for nine months in 1981 and will conduct tests for the last half of 1982, after which Northern States Power will operate the spray dryer and fabric filter. Flakt is conducting a one-year demonstration program at the Jim Bridger Station. The tests are scheduled to be completed in early 1983.

Final acceptance and compliance tests at Montana-Dakota Utilities' Coyote Station are scheduled for this fall. This sodium-based system has been operating since the Spring of 1981. Coyote performance data and operating results are summarized later in this section and are also discussed in detail in Section 3.16 and Section 4.

Four utility systems are scheduled to become operational before the end of 1982: Marquette Board of Light and Power's Shiras Unit 3, Basin Electric's Laramie River Unit 3, Colorado Ute Electric's Craig Unit 3, and United Power's Stanton Unit 1A. Construction is in progress on three other utility systems scheduled for 1983 start-up.

Four new utility systems have been sold since mid-1981. Rockwell International was awarded a contract for a lime-based spray dryer/fabric filter system in late 1981. The system will serve a 270 MWe unit at Sierra Pacific Power's North Valmy Station in Valmy, Nevada. Three parallel dryers, each with three rotary atomizers, will treat 1,200,000 acfm of flue gas from a boiler firing western subbituminous coal. The system will be designed for coal sulfur contents of from 0.4 to 1.5 percent.

TABLE 2-1. SUMMARY OF UTILITY SPRAY DRYING SYSTEMS SOLD (NOVEMBER 1982)

System Purchaser	Station/ Location	Size Gross MWe	 acfm	Status	Vendor[a]
Northern States Power Co.[b]	Riverside, Units 6 and 7 (Minneapolis, MN)	110	640,000 @ 350°F	Operated for 9 mo. in 1981 and for last half of 1982 by vendor. Utility to operate complete system after demo. program.	Joy/Niro
Pacific Power and Light[c]	Jim Bridger, Unit 2, (Rock Springs, WY)	100	389,000 @ 230-240°F	Being operated as a demonstration unit by vendor until early 1983.	Flakt
Otter Tail Power Co. (Montana-Dakota Utilities)	Coyote, Unit 1 (Beulah, ND)	440	1,890,000 @ 285°F	Performance tests completed. Final acceptance and compliance tests scheduled for Fall 1982.	Rockwell/ Wheelabrator -Frye
United Power Assoc.	Stanton, Unit 1A (Stanton, ND)	60	324,500 @ 323°F	September 1982 start-up.	Cottrell Environmental/ Komline-Sanderson
Marquette Board of Light and Power	Shiras, Unit 3 (Marquette, MI)	44	226,000 @ 227-265°F	Start-up scheduled for November 1982.	G.E. Environmental Services
Basin Electric Power Coop.	Laramie River, Unit 3 (Wheatland, WY)	575	2,300,000 @ 286°F	Low electric demand delayed performance tests, expected in late 1982.	Babcock and Wilcox
Colorado Ute Electric Assoc.	Craig, Unit 3 (Craig, CO)	447	1,770,000 @ 245°F	Initial operation in November 1982. Commercial operation in April 1983.	Babcock and Wilcox
Basin Electric Power Coop.	Antelope Valley, Unit 1 (Beulah, ND)	440	2,055,000 @ 318°F	Under construction. May, 1983 start-up.	Joy/Niro
Basin Electric Power Coop.	Antelope Valley, Unit 2 (Beulah, ND)	440	2,055,000 @ 318°F	April 1985 start-up.	Joy/Niro
Tucson Electric Power	Springerville, Unit 1 (Springerville, AZ)	370	1,660,000 @ 256°F	June 1985 start-up.	Joy/Niro
Tucson Electric Power	Springerville, Unit 2 (Springerville, AZ)	370	1,600,000 @ 256°F	June 1986 start-up.	Joy/Niro

(cont.)

TABLE 2-1. (CONTINUED) SUMMARY OF UTILITY SPRAY DRYING SYSTEMS SOLD (NOVEMBER 1982)

System Purchaser	Location	Size Gross MWe	acfm (^{o}F)	Status	Vendor[a]
Platte River Power Authority	Rawhide, Unit 1 (Fort Collins, CO)	280	1,206,000 @ 270^{o}F	December 1983 start-up. Under construction.	Joy/Niro
Sunflower Electric	Holcomb, Unit 1 (Holcomb, KS)	319	1,340,000 @ 260^{o}F	June 1983 start-up. Under construction **3 mo. ahead of schedule.**	Joy/Niro
Sierra Pacific Power	North Valmy (Valmy, NV)	270	1,200,000	1984 start-up.	Rockwell
Grand River Dam Authority-State of Oklahoma	Pryor, Unit 2 (Pryor, OK)	520	1,850,000 @ 250-300^{o}F	March 1985 start-up. August 1985 commercial operation.	Flakt
Northern States Power Company	Sherburne County, Unit 3 (Becker, MN)	860	NA[d]	Awarded in Fall 1982.	Joy/Niro
Cajun Electric	Oxbow, Unit 1 (Coushoutta, LA)	565	NA	Awarded in Fall 1982.	Joy/Niro

[a] Rockwell/Wheelabrator-Frye is no longer a joint venture, but both are offering spray drying systems.
Joy/Niro: Joy takes the lead in utility sales, while Niro takes the lead in industrial sales.
G.E. Environmental Services: Formerly Buell Emission Control Division, Envirotech Corp. Spray dryer supplied by Anhydro A/S.
Cottrell Environmental Sciences supplies fabric filter. Komline-Sanderson supplies spray dryer.

[b] Retrofit system currently being operated as a demonstration unit. Utility has purchased fabric filter, will purchase spray dryer in late 1982.

[c] Currently being operated by vendor, but utility has purchased this retrofit system.

[d] NA = Information not available.

TABLE 2-2. DESIGN FEATURES SUMMARY FOR UTILITY COMMERCIAL SPRAY DRYER SYSTEMS [a]

System [b] (Vendor)	Description	Design Coal Data			SO_2 Removal Guarantee [d]		Solids Recycle ?	Solids Disposal
		Type	HHV; Ash [c]	Sulfur	Removal	Outlet(lb/10^6Btu)		
Riverside, Units 6 & 7 (Joy/Niro)	1 spray dryer with rotary atomizer; lime reagent; reverse air fabric filter.	Varies with test series.			Varies with test series.		Yes	Trucked to landfill.
Jim Bridger, Unit 2 (Flakt)	Reactor with 10 dual-fluid nozzle atomizers; ESP; testing both lime and soda ash.	Western subbituminous	11,600 Btu/lb; 10.0% ash	0.56% avg. 0.8% maximum	Lime: 62-74% Soda ash: 74-86%;	0.3	Variable with test; provisions exist.	Possible mine-mouth disposal.
Coyote, Unit 1 (Rockwell/Wheelabrator-Frye)	4 parallel spray dryers, with 3 rotary atomizers each; initially will use commercial soda ash; reverse-air fabric filter.	North Dakota lignite	7046 Btu/lb; 7.0% ash	0.78% avg.	70% for all fuels	1.2	No	Clay-lined landfill.
Stanton, Unit 1A (Cottrell/Komline-Sanderson)	1 spray dryer with 3 rotary atomizers; lime reagent, reverse-air fabric filter.	North Dakota lignite	7000 Btu/lb; 6.9% ash	0.77% avg. 1.94% maximum	70% or 0.6 lb/10^6Btu; [e] (whichever is lower)		No	Clay-lined pond; water sluice.
Shiras, Unit 3 (G.E. Environmental Services)	1 spray dryer with a single rotary atomizer; lime reagent; reverse-air fabric filter; 3 percent hot gas bypass around dryer.	Western subbituminous	8654 Btu/lb; 10.25% ash	1.5% maximum	80% design removal	0.94	Yes	Landfill.
Laramie River, Unit 3 (Babcock and Wilcox)	4 parallel reactors (1 spare) with 12 "y-jet" nozzle atomizers each; lime reagent; each reactor followed by an ESP; 5 percent gas bypass around dryer.	Wyoming subbituminous	8140 Btu/lb; 8% ash	0.54% avg; 0.81% max.	82% for avg; 78% for max. S coal	0.20	Yes	Lined landfill.
Craig, Unit 3 (Babcock and Wilcox)	4 parallel reactors (1 spare) with 12 "y-jet" nozzle atomizers each; lime reagent, reverse-air fabric filter.	Western subbituminous	8950 Btu/lb; 14% ash	0.7% design coal	87% for design coal	0.20	Yes	Dry landfill.
Antelope Valley, Unit 1 (Joy/Niro)	5 parallel spray dryer (1 spare); single rotary atomizer per dryer; lime reagent; reverse-air fabric filter; 3.2 percent hot gas bypass around dryer.	North Dakota lignite	6600 Btu/lb; 7.8% ash	0.68% avg. 1.22% max.	62% for avg.; 78% for max. S coal	0.78	Yes	Wetted transport to lined landfill.
Antelope Valley, Unit 2 (Joy/Niro)	Same as Antelope 1 above, except no bypass.	Same as Antelope 1			89% for max. S coal	0.39	Yes	Same as Antelope 1.

(continued)

TABLE 2-2. (CONTINUED) DESIGN FEATURES SUMMARY FOR UTILITY COMMERCIAL SPRAY DRYER SYSTEMS

System [b] (Vendor)	Description	Coal Data			SO_2 Removal Guarantee[d]		Solids Recycle?	Solids Disposal
		Type	HHV; Ash[c]	Sulfur	Removal	Outlet (lb/10^6Btu)		
Springerville, Unit 1 (Joy/Niro)	3 parallel spray dryers (no spare); single rotary atomizer per dryer; lime reagent; reverse-air fabric filter; 17.5 percent gas bypass around dryer.	New Mexico subbituminous	8500 Btu/lb; 20% ash	0.69% avg.	61%	0.6	Yes	Natural clay-lined landfill.
Springerville, Unit 2 (Joy/Niro)	Same as Springerville 1	Same as Springerville 1			Same as Springerville 1		Yes	Same as Springerville 1.
Rawhide, Unit 1 (Joy/Niro)	3 parallel spray dryers (1 spare); single rotary atomizer per dryer; lime reagent; reverse-air fabric filter; 10 percent gas bypass around dryer.	Western subbituminous	8500 Btu/lb; 6.0% ash	0.3% avg. 0.44% max.	80%	0.18	Yes	Dry landfill.
Holcomb, Unit 1 (Joy/Niro)	3 parallel spray dryers (1 spare); single rotary atomizer per dryer; lime reagent; reverse-air fabric filter.	Wyoming subbituminous	8313 Btu/lb; 5.6% ash	0.34 % avg.	80%	0.27	Yes	Landfill with fixation.
North Valmy (Rockwell)	3 parallel spray dryers (no spare); 3 rotary atomizers per dryer; lime reagent; reverse-air fabric filter, gas bypass.	Western subbituminous	NR[g]	0.4 to 1.0%	76% for all coal	0.6	Yes	Not reported.
Pryor, Unit 2 (Flakt)	4 reactors in parallel (1 spare), each with 3 rotary atomizers; lime reagent; ESPs; gas bypass.	Western subbituminous	8000-9600 Btu/lb; 7% ash	0.4 to 1.5%	85% for all coal	NR	Provision will exist.	Landfill

---

[a] Some of the information contained in the table, particularly on gas bypass percentage, outlet SO_2 levels, and solids disposal was obtained from a recent report on the status of utility spray drying applications - Reference 1.

[b] Referred to by generating station name as given in Table 2-1. Information for Sherburne County and Oxbow was not available since these systems were only recently awarded.

[c] HHV = high heating value; HHV, % ash reported as average for the design coal.

[d] Where guarantee information was not available, design values are reported.

[e] PSD permit for Holcomb based on 1 percent S coal at 7800 Btu and a 0.48 lb $SO_2/10^6$ Btu outlet emission limit (corresponds to about 91% removal for maximum sulfur coal).

[f] Designed for wide range of coal types.

[g] NR = Not Reported.

TABLE 2-3. SUMMARY OF INDUSTRIAL BOILER SPRAY DRYING SYSTEMS SOLD (NOVEMBER 1982)

System Purchaser/ Location	Size		Status	Vendor[a]
	acfm	lb steam/ hr		
Argonne National Laboratory Argonne, IL	75,000 @ 300°F	170,000	Operational. Passed initial performance tests. Undergoing 60-day reliability and performance tests.	Niro/Joy
Strathmore Paper Company Woronoco, MA	40,000 acfm @ 330°F	85,000	Operational. Turned over to system purchaser. Has achieved removal guarantee.	Mikropul/Koch
Celanese Fibers Company; Cumberland, MD	65,000 acfm @ 350-370°F	110,000	Operational. Turned over to system purchaser. Has achieved removal guarantee.	Rockwell/Wheelabrator-Frye
Container Corporation; *Philadelphia, PA*	94,300 acfm @ 350°F	170,000	Achieved 90% removal guarantee. Final stages of acceptance testing.	Ecolaire, Inc.
University of Minnesota; Units 1 & 2 Minneapolis, MN	120,000 acfm each @ 375°F	40MWe[b] each	Start-up scheduled for late 1982.	Flakt[c]
Austell Box Board Co.; Austell, Georgia	171,000 acfm @ 350°F	250,000	Under construction. Start-up scheduled for November 1982.	Wheelabrator-Frye
General Motors Buick Division Flint, MI	NR[d]	450,000	Under construction. Start-up date not set.	Niro/Joy
Fairchild Air Force Base, Units 1, 2 and 3; Spokane, WA	NR[d]	110,000 each	Under fabrication. Start-up scheduled for late 1983.	Niro/Joy

---

[a] Niro/Joy: Niro takes the lead in industrial sales, while Joy takes the lead in utility sales.
Mikropul/Koch: Mikropul originally sold the Strathmore system, but now operates with Koch Engineering in a joint venture for future spray dryer sales.
Rockwell/Wheelabrator-Frye: (see note, Table 2-1).

[b] Part of cogeneration system.

[c] Originally sold by Kennecott Development Co., which was purchased by Flakt in early 1982.

[d] NR = not reported.

TABLE 2-4. DESIGN FEATURES SUMMARY FOR INDUSTRIAL BOILER SPRAY DRYING SYSTEMS

		Desgin Coal Data			SO_2 Removal Guarantee[c]			
System[a] (Vendor)	Description	Type	HHV, Ash[b]	Sulfur	Removal	Outlet (lb/10^6 Btu)	Solids Recycle?	Solids Disposal
Argonne National Labs. (Niro/Joy)	One spray dryer with single rotary atomizer; lime reagent; pulse-jet fabric filter.	Illinois bituminous	11,800 Btu/lb 8.0% ash	3.5%	78.7%	1.2	Yes	On-site landfill.
Strathmore Paper Co. (Mikropul/ Koch)	One spray dryer with four nozzle atomizers; lime reagent; pulse-jet fabric fiber.	Eastern bituminous	13,000 Btu/lb	2.3 to 3%	75 %	1.2	No	Trucked to off-site landfill.
Celanese Fiber Co. (Rockwell/ Wheelabrator-Frye)	One spray dryer with single rotary atomizer; lime reagent; pulse-jet fabric filter; warm gas bypass.	Eastern subbituminous	NR[d]	2.0% maximum	70% for 1% S coal; 86% for 2% S coal	70 $\frac{lb}{hr}$ SO_2 outlet	No	Trucked to off-site landfill.
Container Corp. (Ecolaire)	One spray dryer with single rotary atomizer; lime reagent; pulse-jet fabric filter.	Eastern subbituminous	NR	1%	Design removal of 90%	NR	Yes	NR
University of Minnesota; (Flakt) Units 1, 2.	Two spray dryers, one has single rotary atomizer, the second has three rotary atomizers; lime reagent; reverse-air fabric filter.	Subbituminous	NR	0.6 to 0.7%	70%[e]	NR	No	NR
Austell Box Board Co. (Wheelabrator-Frye)	One spray dryer with 12 nozzle atomizers; lime reagent; pulse-jet fabric filter.	Bituminous	NR	1.0 to 2.5%	Varies with Sulfur content	1.2	Provisions will exist	NR
General Motors (Niro/Joy)	One spray dryer with single rotary atomizer; lime reagent; fabric filter.	Indiana bituminous	NR	1-3%	70 to 90%	1.2	Yes	NR
Fairchild AFB; Units 1,2,3 (Niro/Joy)	Three spray dryers (one per unit), each with a single rotary atomizer; lime reagent; fabric filter.	Western subbituminous	NR	1%	85%	NR	Yes	NR

[a] Referred to by system purchaser as shown in Table 2-3.

[b] HHV = high heating value, Btu/lb; HHV and % ash reported as average for the design coal.

[c] Where guarantee information not available, design values are reported.

[d] NR- not reported

[e] At a reagent ratio of 1.0.

The system will have solids recycle and warm gas bypass. The SO_2 removal guarantee is 76 percent.

In May 1982, Flakt announced it had received a contract for a spray dryer/ESP system to serve a Grand River Dam Authority (State of Oklahoma 520 MWe coal-fired boiler near Pryor, Oklahoma. The lime-based system will treat 1,850,000 acfm of flue gas in four parallel reactors (one spare). Each reactor will be equipped with three rotary atomizers. Provisions for warm gas bypass and solids recycle will be included. The boiler will fire a western subbituminous coal with a sulfur content between 0.4 and 1.5 percent. The SO_2 removal guarantee is 85 percent. System start-up is scheduled for March 1985.

Joy/Niro was awarded the Cajun Electric Oxbow and Northern States Power Sherburne County systems this fall. No details on these systems are available yet. The 860 MWe Sherburne County system is the largest spray drying system sold to date.

Table 2-2 summarizes the design features of the utility spray drying systems. All are designed for low to moderate sulfur coal (1.5 percent sulfur or less), except for a maximum design value of 1.94 percent sulfur lignite at United Power's Stanton Station. SO_2 removal guarantees range from 61 to 91 percent. Lime will be used in all of the systems except Coyote and Jim Bridger, although tests with lime will be conducted at Jim Bridger. Warm or hot gas bypass is used on a site-specific basis. Solids recycle is included in all but one of the 13 lime-based systems. In addition to providing the opportunity for reuse of unreacted lime or available fly ash alkalinity to reduce fresh lime requirements, solids recycle improves the operability of rotary atomizers (See Section 4.5).

The dry product solids/fly ash mixture generated by the spray drying systems will be disposed of in landfills at most of the utility locations. Available information indicates that for some of the landfill operations the solids will be wetted before transfer to the landfill, presumably to reduce dust problems (1). Most of the vendors' utility system contracts do not include responsibility for waste solids disposal operations. An exception is Joy/Niro's contract with Sunflower Electric. In this case, Joy/Niro will design and supply the equipment for a fixated solids disposal process.

Industrial Boilers

Table 2-3 shows the eight industrial boiler commercial spray drying systems sold to date. (A few vendors have also sold spray drying systems for incinerators or kilns, but these applications are not covered in detail in this report.) Table 2-3 shows that the industrial systems range in size from one 85,000 lb steam/hr boiler at Strathmore Paper Co.'s Woronoco, Massachusetts plant to two 40 MWe boilers that are part of a cogeneration system at the University of Minnesota in Minneapolis.

Four of the industrial boiler systems are operational. All of these systems have been reported to have achieved their performance guarantees. The Celanese and Strathmore systems are being operated by their respective purchasers. The Argonne system will be turned over after final 60-day performance tests scheduled for fall 1982, and the Container Corporation system is in the final stages of acceptance testing. The University of Minnesota and Austell Box Board systems are both scheduled to start up before the end of 1982.

The two new industrial boiler systems sold since late 1981 were both awarded to Joy/Niro. The lime-based systems are identical to previous Joy/Niro designs, incorporating spray dryers with single rotary atomizers and solids recycle. Both of the systems will use pulse-jet fabric filters. The General Motors' 450,000 lb steam/hr boiler will fire an Indiana bituminous coal with a sulfur content of between 1 and 3 percent. A 1 percent sulfur western subbituminous coal will fuel the three 110,000 lb steam/hr boilers at the Fairchild Air Force Base location. Each boiler will be equipped with a separate spray dryer/fabric filter system.

Table 2-4 summarizes the design features of the industrial boiler systems. The design coal sulfur contents in the industrial applications, all of which will use lime, range from 0.6 to 3.5 percent. Sulfur dioxide removal guarantees range from 70 to 90 percent, with at least four of the systems designed to meet a 1.2 lb SO_2/million Btu (heat input) emission limit. Five of the eight systems include solids recycle. Only one of the systems (Celanese) has gas bypass and all but one of the industrial systems will have pulse-jet fabric filters. The larger University of Minnesota system will employ a reverse-air fabric filter. Since pulse-jet fabric filters generally operate at higher air-to-cloth ratios, they are less expensive than reverse-air filters up to a certain size [generally below 100,000 acfm (2)]. Above the cutoff, which is a function of site-specific factors, pressure drop costs begin to offset the savings associated with the higher air-to-cloth ratios of pulse-jet designs.

Off-site landfill disposal of the waste solids will be used in most of the industrial applications since there is typically little land area available for on-site disposal.

Spray Drying System Vendors

Table 2-5 shows the firms currently offering utility and/or industrial boiler spray drying systems. Since the last survey was published in the Fall of 1981, several changes have occurred within this group of vendors:

- Flakt, Inc. purchased the Kennecott Environmental Products Division of Carborundum, Inc. and with it acquired the University of Minnesota system Kennecott had sold.
- Mikropul, Inc. and Koch Engineering are now offering spray drying systems in a joint venture.
- General Electric purchased the Buell Emission Control Division of Envirotech Corporation and this group is now referred to as G.E. Environmental Services, Inc.

TABLE 2-5. FIRMS OFFERING A COMMERCIAL SPRAY DRYING FGD SYSTEM

Firm or Team of Firms	Design Features[a]		Number of Systems Sold in U.S.	
	Spray Dryer[b]	Atomization	Utility	Industrial
Babcock and Wilcox (B&W)	Horizontal dryer with hoppers for solids collection.	12 "Y-jet" air-atomized nozzles for each full-size reactor.	2	Does not plan to bid
Combustion Engineering, Inc.	Two-point discharge vertical dryer.	Multiple (extenally-mixed) sonic nozzle atomizers per dryer	None	None
Cottrell Environmental Sciences, Inc. and Komline-Sanderson Inc.	Two-point discharge vertical dryer.	Multiple (3) rotary atomizers per dryer. Nozzle atomizers for sodium-based systems.	1	None
Ecolaire, Inc.	Two-point discharge vertical dryer.	Single rotary atomizer per dryer. Have tested with nozzle atomizers.	None	1
Flakt, Inc.	Two-point discharge vertical dryer.	Multiple atomizers per dryer. Three rotary per dryer for full-scale utility module. Ten air-atomized nozzles/dryer design for Jim Bridger **demonstration unit.**	2	1
G.E. Environmental Services	Two-point discharge vertical dryer.	Single rotary atomizer per dryer.	1	None
Joy Manufacturing Company and Niro Atomizer, Inc.	Two-point discharge vertical dryer with central gas disperser.	Single rotary atomizer per dryer.	9	3^e
Mikropul, Inc. and Koch Engineering, Inc.	Two-point discharge vertical dryer with "proprietary" internals	Multiple air-atomized nozzles per dryer. Investigating rotary atomizers.	None	1
Rockwell International	Single-point discharge vertical dryer.	Multiple (3) rotary atomizers per dryer for utility. Single rotary atomizer per dryer for industrial.	2^c	1^d
Wheelabrator-Frye, Inc.	Vertical dryer with nozzle atomizers or vertical with rotary atomizers.	Multiple air-atomized nozzles for industrial. Single rotary atomizer per dryer for utility or large industrial.	1^d	2^c

---

Footnotes

[a] Based primarily on commercial systems sold to date and reported R&D activities. Vendors may offer other design features.

[b] Two-point discharge dryers have bottom discharge for solids that drop out in dryer.

[c] One sold by Rockwell/Wheelabrator-Frye joint venture, other sold independently.

[d] Sold by Rockwell/Wheelabrator joint venture.

[e] The Fairchild system will have 3 units.

Table 2-5 shows that a number of vendors offer both nozzle and rotary atomizers. Two vendors, Flakt and Rockwell, offer multiple rotary atomizer per dryer designs for utility systems. Some vendors have recently advocated the use of nozzle atomizers for industrial boiler systems less than about 200,000 to 250,000 acfm. However, these vendors still tend to favor rotary atomizers for larger systems.

Conventional vertical flow dryers are still the most common design, although Babcock and Wilcox offers a horizontal flow dryer design.

Performance Data

Table 2-6 summarizes recently published performance and compliance test data from operating full-scale spray dryer FGD systems. Data from the Argonne and Strathmore systems represent high sulfur coal applications. Argonne reported that a reagent ratio of about 1.4 was required for 90 percent SO_2 removal at a 23°F approach to saturation and a recycle ratio of about 2 lb recycle solids per lb of fresh lime (3). At Strathmore, a 1.9 reagent ratio enabled 92.4 percent average SO_2 removal (no solids recycle) with about a 25°F approach (4).

Figure 2-1 shows recently published data on SO_2 removal as a function of reagent ratio for several different lime-based systems. Test conditions for the data presented are given in Table 2-7. Data from earlier EPA-funded test work on the Comanche and Martin Drake pilot-scale spray dryer systems are shown for comparison in Figures 2-2 and 2-3, respectively.

Spray Dryer System Costs

Table 2-8 shows a summary of utility system capital cost data as reported by the Electric Power Research Institute (1). These data show capital costs ranging from $60 to $189/kW, depending on contract scope, system size, and other site-specific factors.

Table 2-9 presents capital cost data for a few of the industrial systems. In addition, annual operating costs have been recently reported for the Strathmore system(5). The Strathmore costs, as shown below, are expressed in terms of dollars per ton of coal burned:

TABLE 2-6. PERFORMANCE AND COMPLIANCE TEST DATA FOR SPRAY DRYING SYSTEMS

System/Vendor	Performance/Compliance Test Data				Comments
Argonne Labs/Joy-Niro	Boiler Load (% MCR)[a]	Inlet SO_2 (lb/10^6 Btu)	Outlet SO_2 (lb/10^6 Btu)	SO_2 Removal (%)	Lime reagent, solids recycle, 3% S coal, EPA Method 6 tests.
	35	6.69	1.36	79.7	
	70	5.93	0.60	89.9	
	82	6.13	0.27	95.6	
Strathmore/Mikropul-Koch	Test No.	Inlet SO_2 (ppmv)	Outlet SO_2 (ppmv)	SO_2 Removal (%)	Lime reagent, no solids recycle, 3.79% S coal. EPA Method 6 tests. About 75% boiler load for all tests.
	1	2057	132	93.6	
	2	1948	65	96.7	
	3	2014	195	90.3	
	4	1974	166	91.6	
	5	1984	196	90.1	
	6	2016	156	92.3	
	avg.			92.4	
Jim Bridger/Flakt	Reagent	SO_2 Removal (%)		Guarantee Removal (%)	EPA Method 6 tests, about 0.6% S coal.
	Soda ash	88.3		86.5	
	Lime with recycle	90.8		74	
	Lime with no recycle	64.1		62	
Coyote/Rockwell-Wheelabrator-Frye	Met performance guarantee of 70% SO_2 removal at 75% reagent utilization.				Soda ash reagent. Recent data showed 70% removal at reagent utilizations of 95% or greater.

[a] MCR - maximum rated capacity.

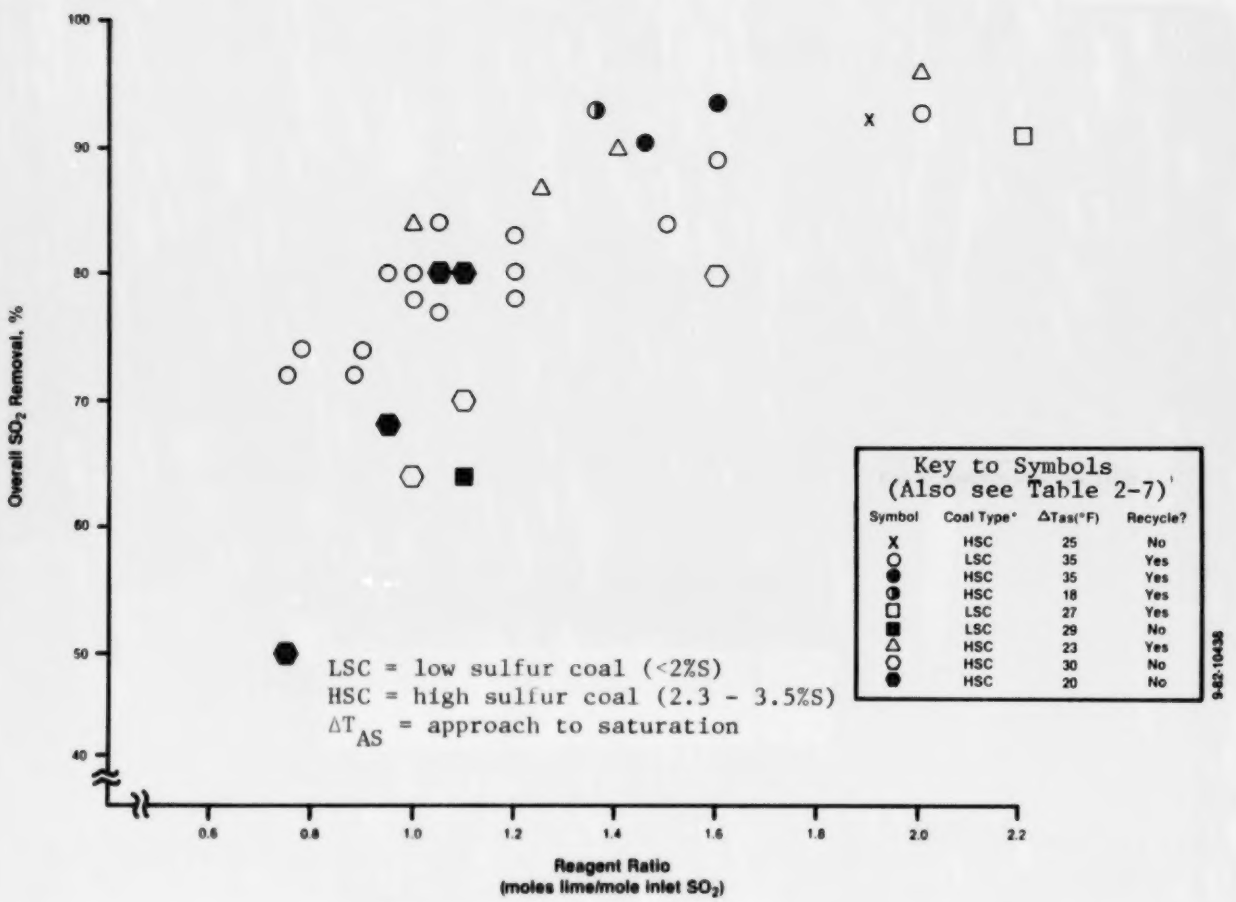


Figure 2-1. Comparison of overall SO_2 removal data for various lime-based spray dryer FGD systems.

TABLE 2-7. PROCESS CONDITIONS FOR DATA SHOWN IN FIGURE 2-1.

Symbol from Figure 2-1	System Description[a]	Coal Type	%S	Process Conditions Inlet SO_2 (ppmv)	Inlet Gas Temp. (°F)	ΔT_{AS} (°F)	Recycle
○	Riverside Station: 110 MWe unit; 680,000 acfm; 46-ft. diameter dryer; rotary atomizer; fabric filter	Colstrip coal blended with petroleum coke	1.2	850-1000	280-315	35	Yes
●	Riverside	Illinois bituminous	3.5	~2000	316-331	32-35	Yes
◐	Riverside	Illinois bituminous	3.5	~2000	~315	18	Yes
□	Jim Bridger Station; 100 MWe unit; 389,000 acfm; ten dual-fluid nozzle atomizers; ESP	Western sub-bituminous	~0.6	NR[b]	229	27	Yes
■	Jim Bridger	Western sub-bituminous	~0.6	NR[b]	238	29	No
X	Strathmore: 85,000 lb steam/hr; 40,000 acfm; 14.5-ft diameter dryer; rotary atomizer; fabric filter	Eastern bituminous	3.8	~2000	~330	25	No
△	Argonne Labs: 170,000 lb steam/hr boiler; 75,000 acfm; 25-ft diameter dryer; rotary atomizer; fabric filter.	Illinois bituminous	3.0	~2200	~300	23	Yes
⬡	PETC: 500 lb/hr pulverized coal furnace; 7-ft diameter dryer; rotary atomizer; fabric filter	West Virginia bituminous	3.1	~2200	~400	30	No
⬢	PETC	West Virginia bituminous	3.1	NR	NR	20	No

[a] Riverside system is a Joy/Niro design. See Section 3-13.
Jim Bridger system is a Flakt design. See Section 3-11.
Argonne system is a Joy/Niro design. See Section 3-13.
See Section 3-6 for description of PETC system.

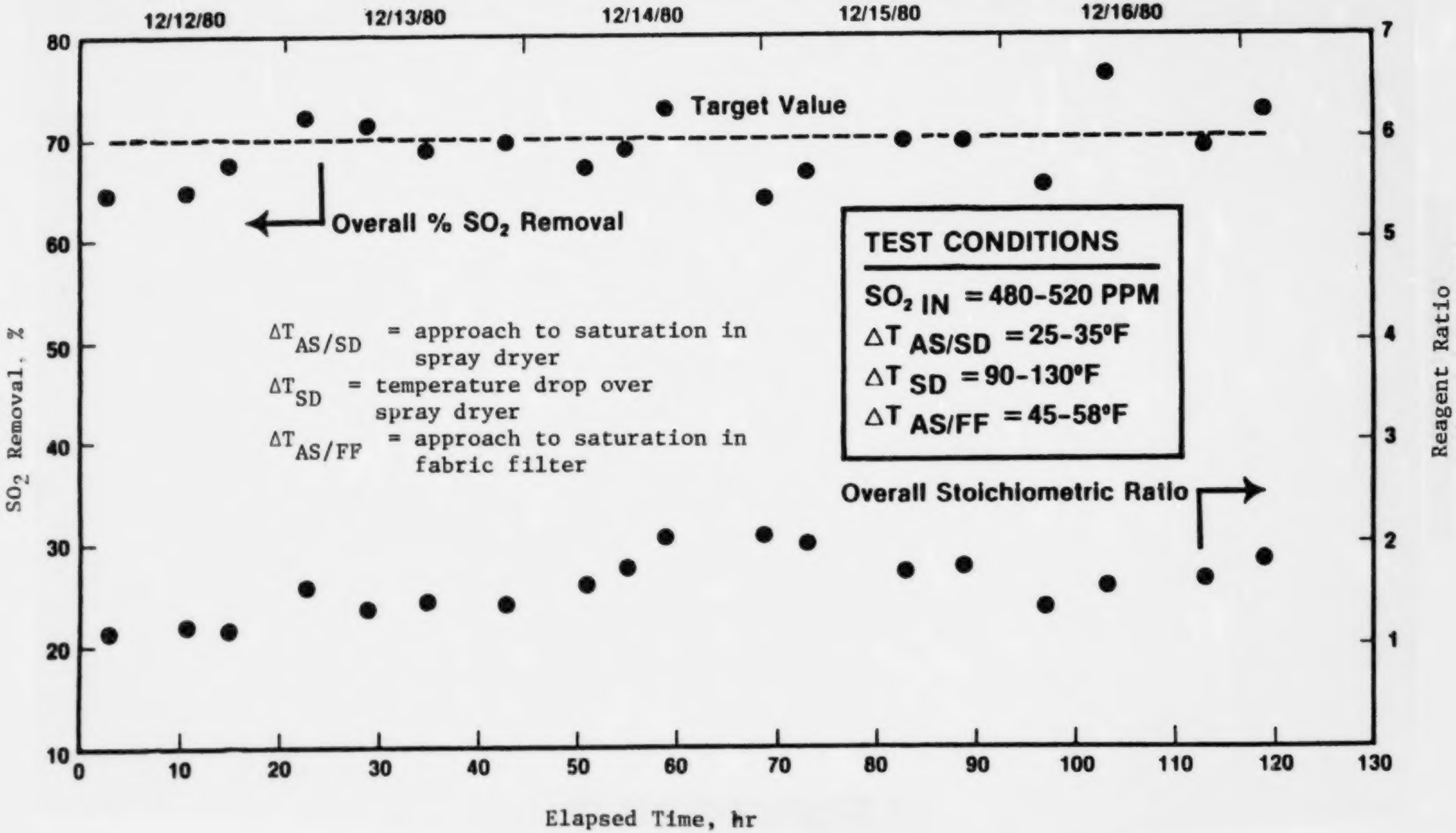


Figure 2-2. SO_2 removal data - Comanche pilot spray dryer tests.

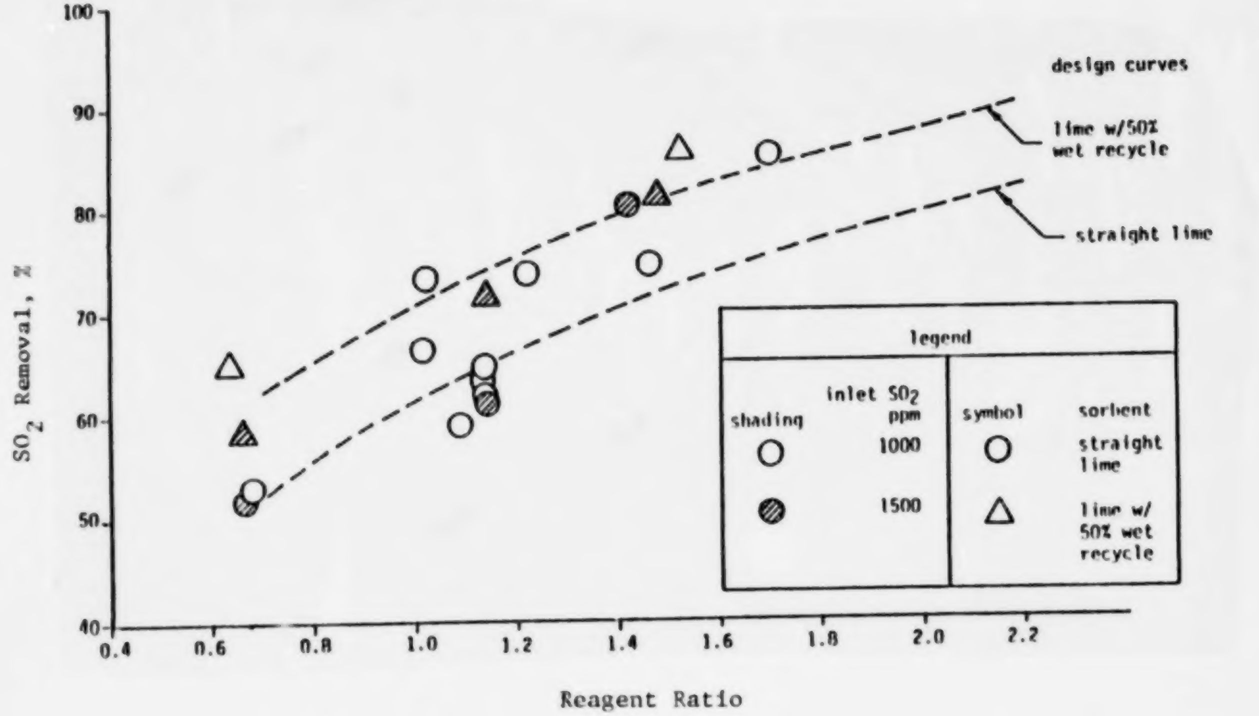


Figure 2-3. SO_2 removal data - Martin Drake pilot spray dryer tests.

TABLE 2-8. REPORTED UTILITY SPRAY DRYER SYSTEM CAPITAL COSTS

Unit/Utility	Contract Award Date	Bid Type	Capital Cost $	Capital Cost $/kW	Contract Scope Includes	Contract Scope Excludes
Coyote 1 Otter Tail Power	4/77	Performance, One Bidder	$36,000,000	84	Supply, Erection, Startup	Foundations, Ash Handling System
Antelope Valley 1 Basin Electric Power	9/78	Competitive, Dry Only	$50,000,000	114	Supply, Erection, Foundations	Lime Storage
Riverside 6, 7 Northern States Power	10/79	Negotiated	NR[a]	NR[a]	Supply, Erection[b]	Spray Dryer
Laramie River 3 Basin Electric Power	11/78	Competitive, Dry Only	$36,000,000	63	Supply, Erection	Foundations
Springerville 1 Tucson Electric Power	1/80	Competitive, Dry Only	$22,000,000	60	Supply Only	Foundations, Erection
Springerville 2 Tucson Electric Power	1/80	Competitive, Dry Only	$22,000,000	60	Supply Only	Foundations, Erection
Stanton 10 United Power	1/80	Competitive, Dry Only	$ 5,700,000	95	Supply, Erection	Foundations, Support Steel
Craig 3 Colorado-Ute	3/80	Competitive, Dry Only	$45,000,000	100	Supply, Erection	NR
Rawhide 1 Platte River Power	3/80	Competitive, Dry Only	$27,000,000	70	Supply, Erection	None
Holcomb 1 Sunflower Cooperative	4/80	Competitive, Wet or Dry	$59,700,000	189	Supply, Erection, Waste Disposal	None
Antelope Valley 2 Basin Electric Power	9/80	Competitive, Dry Only	$54,000,000	123	Supply, Erection, Foundations	Lime Storage
Shiras 3 City of Marquette, MI	10/80	Competitive, Dry Only	$ 6,800,000	154	Supply, Erection, I.D. Fan	Foundations
Jim Bridger 2 Pacific Power and Light	3/81	Performance	NR	NR	Supply, Erection	Foundations

[a] NR = Not Reported

[b] Project is co-funded by Joy and Northern States Power, which has the option to purchase spray dryer.

Source: Reference 1

TABLE 2-9. INDUSTRIAL BOILER SPRAY DRYING SYSTEMS-REPORTED CAPITAL COSTS

System	Size (acfm)	Capital Cost	\$/acfm
Celanese Fibers Co.	65,000	\$1,250,000[a]	\$19.23
Strathmore Paper Co.	40,000	\$1,400,000[a,b]	\$35.00
University of Minnesota	2 @ 120,000 each	\$3,300,000[a,c]	\$13.75

[a] Stern, J.L. "Dry Scrubbing for Industrial Flue Gas Desulfurization: State-of-the-Art, 1980." (Presented at the 89th National Meeting of AICHE, Portland, Oregon, August 17-20, 1980.)

[b] From "ground-up" (1979 \$).

[c] 1980 \$.

Item	$/ton coal burned (5)
Lime (delivered)	8.07
Waste solids handling	2.27
Landfill fees	0.37
Anti-floculant for lime slurry	0.22
Contract maintenance	0.34
Labor (3-man crew)	2.40
	$13.67/ton coal burned

Lime spray dryer/fabric filter cost data have also been reported in a recent EPA report (6). These data are based on utility system estimates developed by the Tennessee Valley Authority (TVA) and industrial system costs used in EPA's development of the industrial boiler NSPS. Figures 2-4 through 2-9 present the capital and operating cost estimates as a function of boiler size. Table 2-10 summarizes the design and economic premises used to develop the costs.

Another source of utility spray dryer system cost data is a 1980 EPRI report (7). Table 2-11 presents the major premises used in that study, while Table 2-12 shows the FGD system design parameters used. Table 2-13 lists the raw material and utility requirements. Capital costs, first-year operating costs, and levelized revenue requirements for 1000 MWe capacity plants burning either 4 percent sulfur eastern coal or 0.48 percent sulfur western coal are shown in Tables 2-14 through 2-16.

It is beyond the scope of this report to compare these estimates since there may be significant differences in the economic and/or design premises used to develop the costs. The reader should refer to the referenced reports for complete descriptions of how the costs were developed. The EPA and EPRI reports (References 6 and 7) also contain cost data for other types of FGD systems that are directly comparable to the respective spray dryer system costs.

Future Commercial Activities

Table 2-17 shows the utilities reported to be currently considering dry FGD for new plants (8). Spray drying is still being considered primarily for low sulfur coal applications.

2.2.2 Research and Development Activities

Table 2-18 shows the status of four recent spray drying research and development programs. Results of EPA-funded tests at Martin Drake, DOE tests at PETC, and the EPRI-funded pilot and laboratory tests were presented at the EPA/EPRI FGD Symposium held in May 1982. The final report on tests conducted for EPA at Comanche is scheduled for publication before the end of 1982.

TABLE 2-10. MAJOR PREMISES FOR EPRI SPRAY DRYER COSTS

Cost estimates are for new units. Developed from Bechtel, Inc. and Niro Atomizer, Inc. estimates.

Costs are based on the following SO_2 removal levels (1978 NSPS):

- 85% SO_2 removal
- 1.2 lb $SO_2/10^6$ Btu maximum emissions
- 0.2 lb $SO_2/10^6$ Btu minimum emissions

All costs are in July 1, 1978 dollars.

The following bases were used to calculate annual O&M costs:

- Operating labor	$12.50/man-hour
- Maintenance labor	0.5% of general facilities cost
- Administration and support	$12.50/man-hour
- Process water	$0.40/thousand gallons
- Electricity	$0.03/kWh
- Lime	$34/ton

Source: Reference 7.

Coal sulfur content, 3.5%; 90% SO_2 removal ———
Gas flow rate for 3.5% S coal is 0.82 times the rate shown on the scale below.

Coal sulfur content 0.7%; 70% SO_2 removal – – – – –

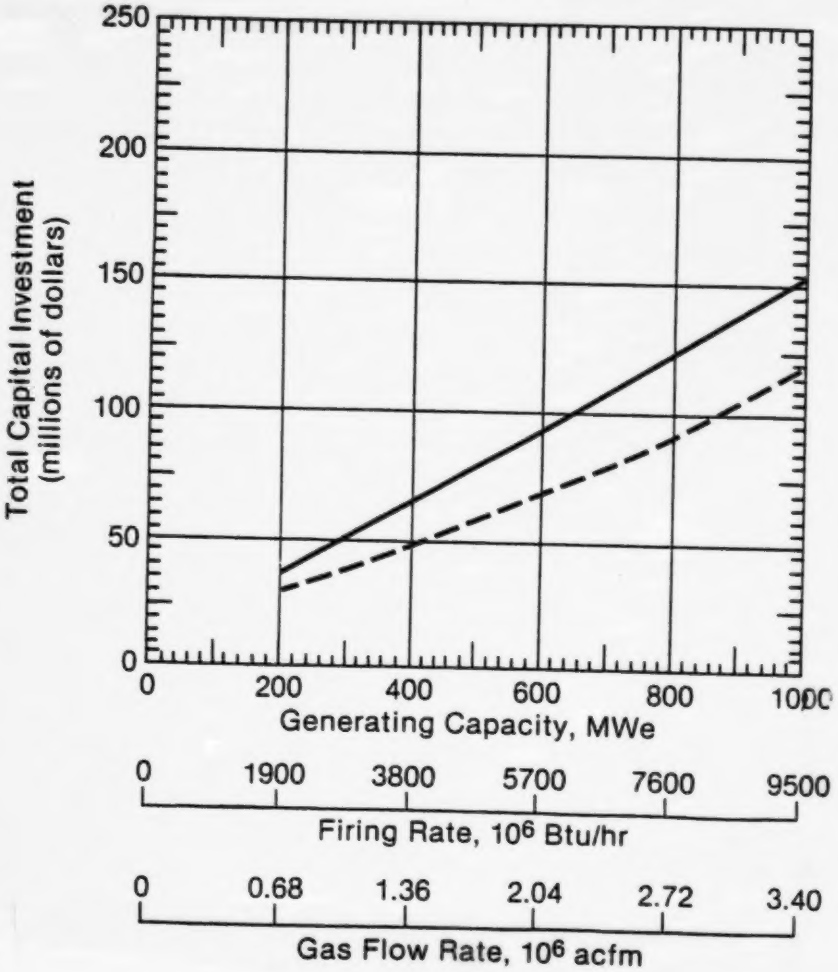


Figure 2-4. Utility system capital cost (1980$) lime spray dryer/fabric filter.
Source: Reference 6.

Figure 2-4 Utility System Capital Cost ($1980) Lime Spray dryer/fabric filter

Source: Reference 6

Coal sulfur content, 3.5%; 90% SO_2 removal ———
Gas flow rate for 3.5% S coal is 0.82 times the rate shown on the scale below.

Coal sulfur content, 0.7% 70% SO_2 removal – – – –

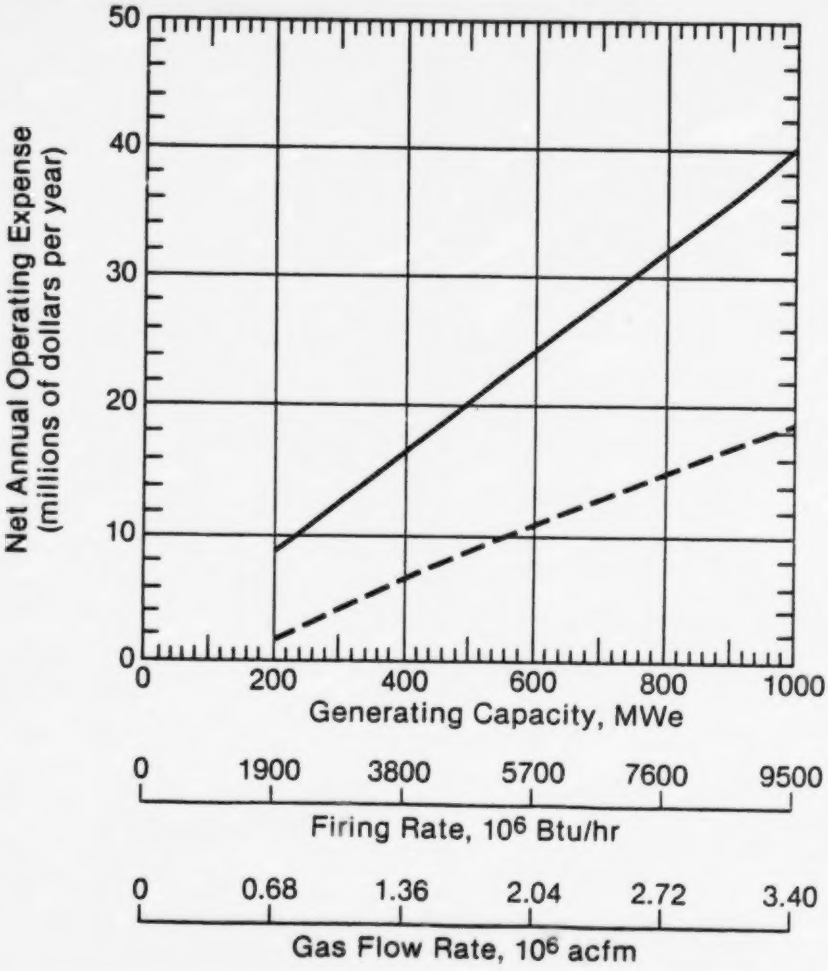


Figure 2-5. Lime spray dryer/fabric filter - utility system annual costs (1980$).

Source: Reference 6.

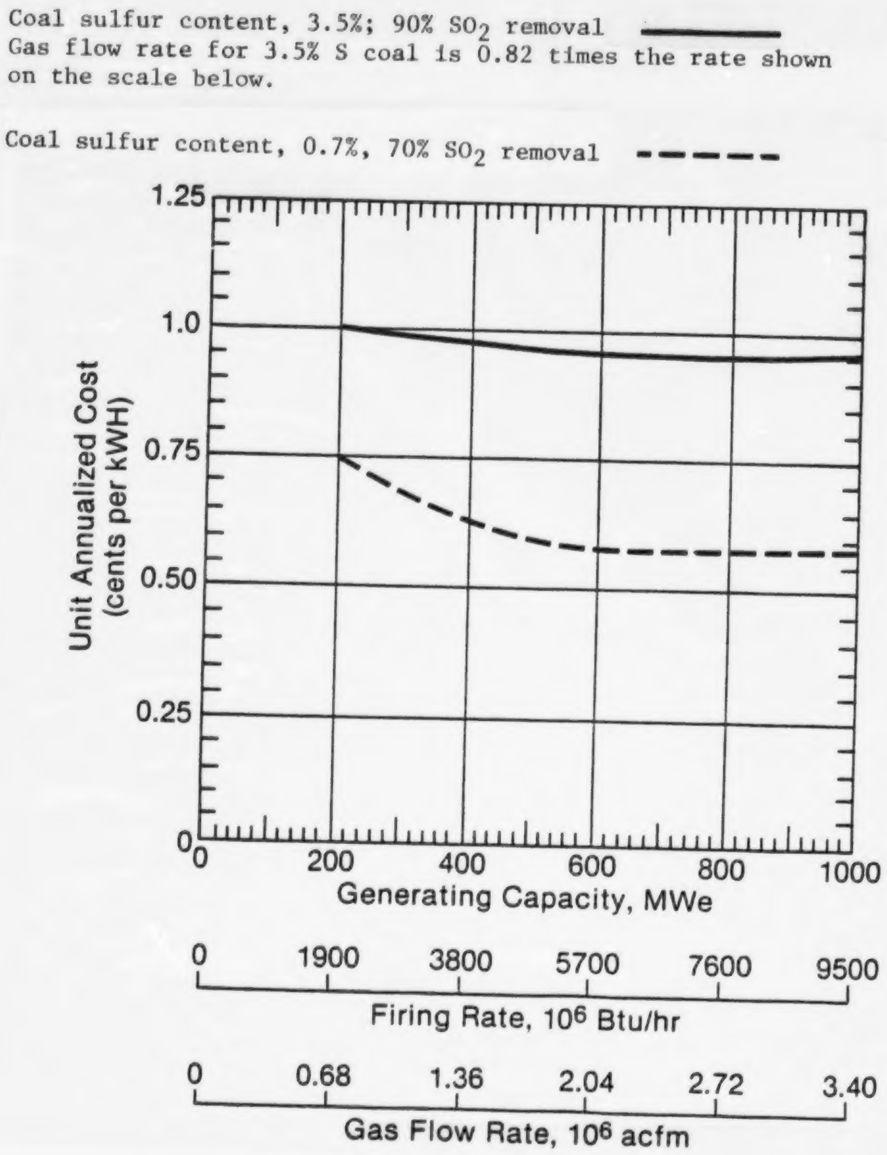


Figure 2-6. Lime spray dryer/fabric filter - utility system annualized costs (1980$).
Source: Reference 6.

1

Figure 2-6. Lime spray Dryer/Fabric Filter
Utility System Annualized Costs ($1980)

Source: Reference 6

Coal sulfur content, 0.7%; 70% SO_2 removal

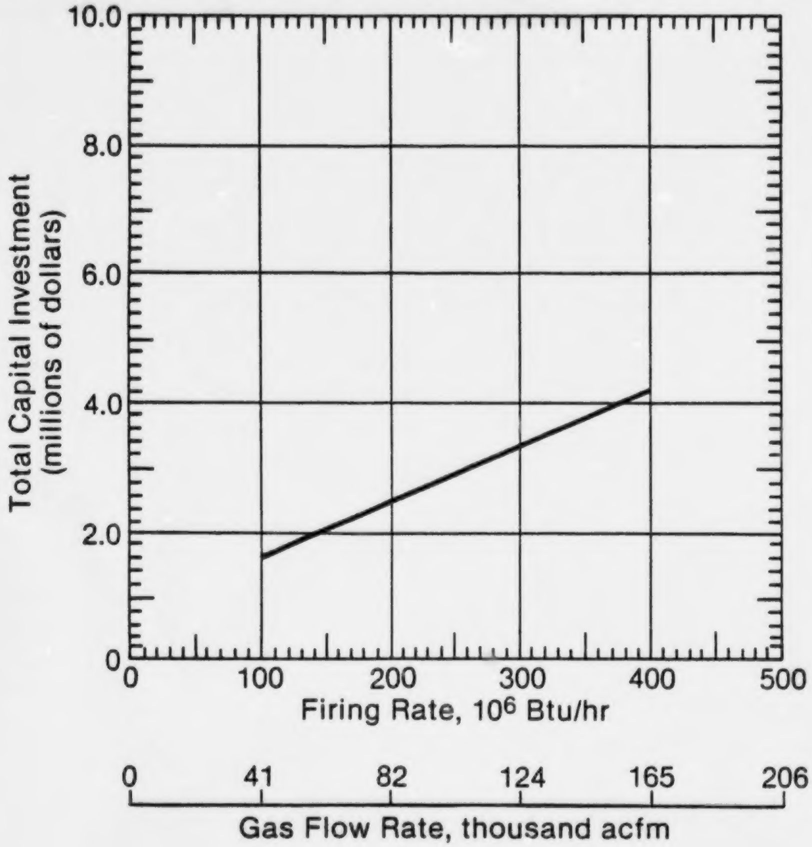


Figure 2-7. Lime spray dryer/fabric filter - industrial system capital costs (1980$).
Source: Reference 6.

Figure 2-7. Lime spray dryer/fabric filter
Industrial system capital cost (1980)

Source: Reference 6

Coal sulfur content, 0.7%; 70% SO_2 removal

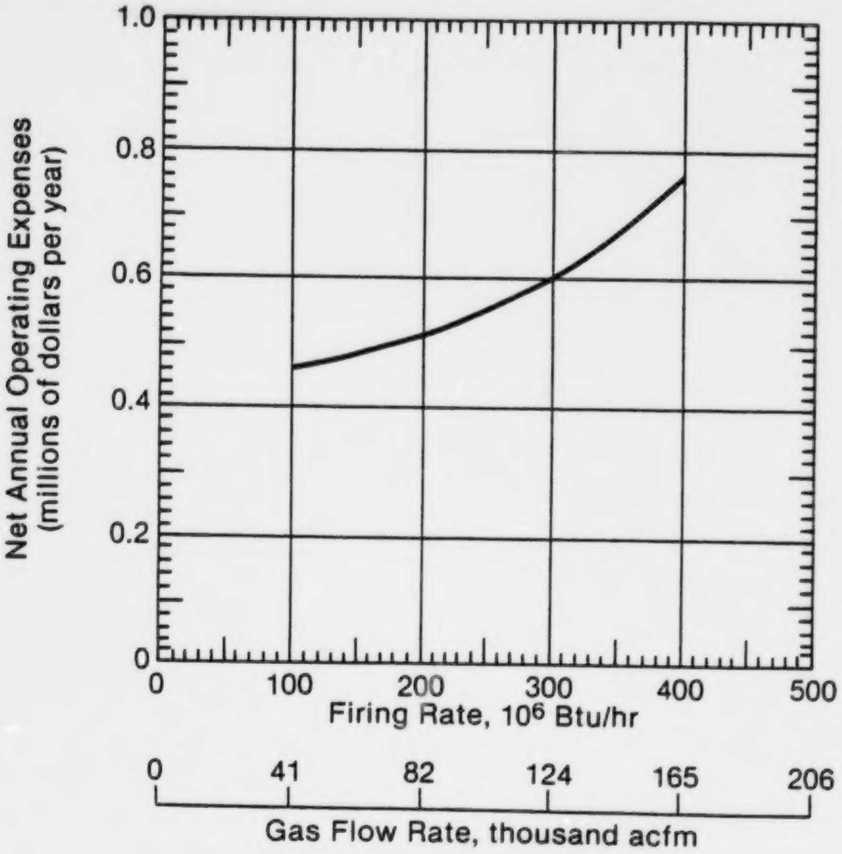


Figure 2-8. Lime spray dryer/fabric filter - industrial system annual operating costs (1980$).
Source: Reference 6.

Figure 2-8. Lime Spray dryer/Fabric Filter—
Industrial System annual operating cost (*1980)
Source Reference 6.

Coal sulfur content, 0.7%; 70% SO_2 removal

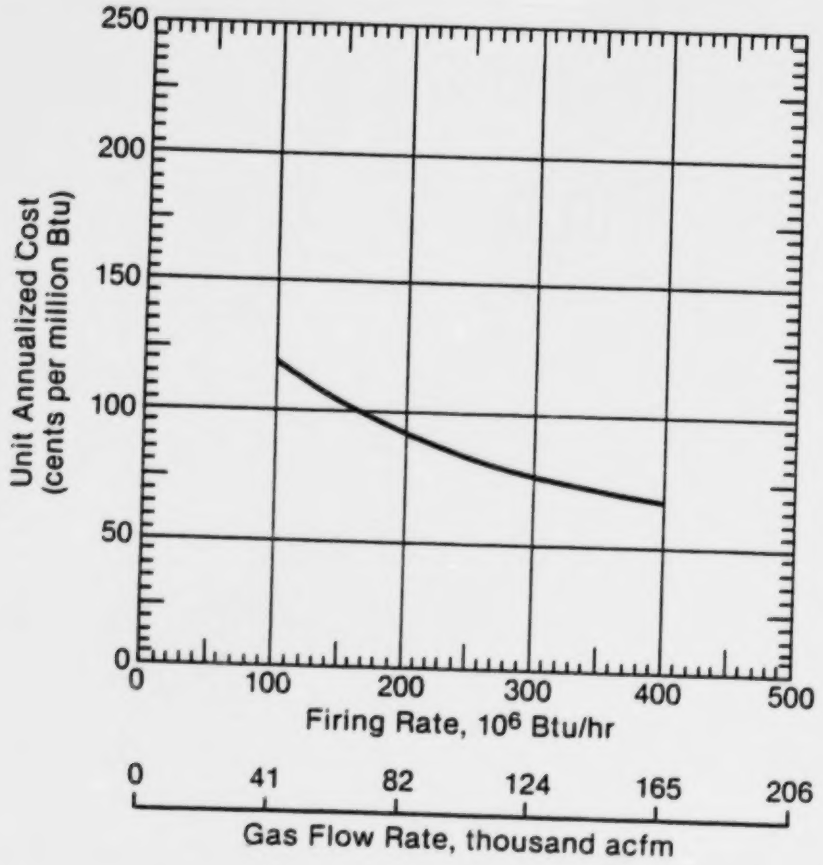


Figure 2-9. Lime spray dryer/fabric filter - industrial system annualized costs (1980$).
Source: Reference 6.

Figure 2-9 Lime spray dryer/fabric filter -
Industrial system annualized costs (1980$)
Source: Reference 6.

TABLE 2-11. BASES FOR EPA UTILITY AND INDUSTRIAL SPRAY DRYER COSTS

Utility Systems

- Cost estimates are for new units.
- Costs are based on 70% SO_2 removal (0.6 $lb/10^6$ Btu controlled emissions) and a low sulfur eastern coal with the following properties: 0.7% S, 15% ash, 11,700 Btu/lb.
- Plant heat rate is 9500 Btu/kWh.
- Costs are derived from TVA 500 MWe case. Curves are based on calculations for 200, 500 and 1000 MWe cases.
- Spray dryers have rotary atomizers; 84% of gas is treated in spray dryers at 83% removal, for an overall SO_2 removal of 70%. Partial bypass is used to reheat gas entering fabric filter. Stack gas exit temperature is 175°F.
- Costs for a reverse-air fabric filter (air-to-cloth ratio of 2.5:1) are included.
- Reagent stoichiometry is assumed to be 1.0 moles lime per mole of inlet SO_2.
- System redundancy includes one spare dryer, redundant reagent preparation area, and SO_2 emergency flue gas bypass.
- Costs include all ductwork associated with system.
- Waste solids are transported one mile to landfill. Landfill is assumed to have clay liner. All capital and operating costs for landfill are included in system costs.
- 30-year plant life, 5500 hr/yr operation (65 percent operating factor).
- Midwest location.

Industrial Systems

- Cost estimates are for new units.
- Costs are based on 70% SO_2 removal and a low sulfur eastern coal with the following properties: 0.7% S, 15% ash, 11,700 Btu/lb.
- Cost curves drawn from calculations for 100, 200, and 400 million Btu/hr cases.
- Spray dryer equipped with rotary atomizer, and designed to treat 84% of the flue gas as 83% removal for an overall removal of 70%. Partial bypass used to reheat gas entering fabric filter. Stack gas exit temperature is 175°F.
- Costs for a reverse-air fabric filter (air-to-cloth) ratio of 2.0:1) are included.
- System redundancy includes spare pumps.
- Costs include all associated duct work.
- Waste solids trucked to off-site landfill. Landfill capital and operating costs not included in system (only charge per ton of waste disposed).
- 30-yr plant life, 5256 hr/yr operation (60 percent operating factor).
- Midwest location.

Source: Reference 6.

TABLE 2-12. LIME SPRAY DRYER/FABRIC FILTER PROCESS SYSTEM PARAMETERS FOR EPRI COSTS

Data for 500 MW Unit
(Maximum Load Conditions)

	Units	Eastern Coal	Western Coal
Flue gas flow rate (270°F, 13 in. w.g.)	10^3 acfm	1927	2085
Number of spray dryers	ea.	5	5
Capacity per spray dryer	%	25	25
Gas flow per spray dryer	10^3 acfm	482	521
Stoichiometric ratio[a]	-	1.35	1.25
Product recycle rate[b]	%	13.3	61.4
Outlet gas temperature	°F	158	166
Dew point temperature	°F	123	131
Spray dryer pressure drop	in. w.g.	4	4
FGD system outlet gas flow rate	10^3 acfm	1720	1890
Baghouse design cloth ratio	ft/min	2.5	2.5
Total compartments	-	34	36
Compartments cleaned simultaneously	-	2	2
Compartments allowed for maintenance	-	2	2
Compartments allowed for maximum bypass flow	-	4	4
Baghouse pressure drop	in. w.g.	8	8
Total pressure drop	in. w.g.	12	12
Gas flow at ID fan inlets	10^3 acfm	1757	1930

Source: Reference 7.

[a] Moles Ca input/mole SO_2 removed - corresponding ratios based on inlet SO_2 are 1.15 and 1.05, corresponding to utilization rates of 74 percent and 72 percent, respectively.

[b] Weight percent of the total solids leaving the spray dryer.

TABLE 2-13. SPRAY DRYER/FABRIC FILTER PROCESS RAW MATERIALS AND UTILITY REQUIREMENTS FOR EPRI COSTS

Data for 500 MW Unit
(Maximum Load, Average Sulfur)

	Units	Eastern Coal	Western Coal
Raw Material			
Lime	tons/hr	23.4	3.3
Utilities			
Electricity			
Raw material receiving, storage and preparation	kW	490	70
Absorption	kW	1600	1700
Fans	kW	3035	3335
Particulate Removal Credit	kW	(1960)	(3645)
Total	kW	3165	1460
Process Water	10^3 gal/hr	19.9	19.3
Waste Materials			
Reaction Products	tons/hr	43.1	6.2
Ash	tons/hr	31.6	16.4
Combined Wastes	tons/hr	74.7	22.6
	yd^3/hr	69.2	21.0
Incremental Heat Rate Penalties			
Steam (basis gross heat rate)	%	None	None
Electricity (basis unit net rating)	%	0.63	0.29
Corrected Net Heat Rate	Btu/kWh	9,622	9,932
Variation from Base	%	-3.65	-3.51

Source: Reference 7.

TABLE 2-14. LIME SPRAY DRYER/FABRIC FILTER - UTILITY SYSTEM CAPITAL COSTS

Basis: **2x500 MW, New Plant**
70% Capacity Factor, 6132 hr/yr
Eastern Coal: Illinois, St. Clair
4.0% Sulfur, 1,927,000 acfm/unit
Western Coal: Wyoming, Campbell
0.48% Sulfur, 2,085,000 acfm/unit
July 1, 1978 Costs for a July 1, 1980 Plant Startup

	$/kW	
	Eastern Coal	Western Coal
Raw Material Receiving & Storage	1.5	0.4
Feed Preparation & Storage	5.1	2.0
Flue Gas Treatment	78.6	73.2
Particulate Removal Credit	(37.5)	(58.1)
Waste Disposal	5.2	1.0
Flue Gas Supply	5.0	6.0
Total Process Capital	57.9	24.5
General Facilities	7.2	3.1
Engineering, H.O.,* Fees	7.2	3.1
Project Contingency	10.8	4.6
Process Contingency	11.6	2.3
Total Plant Investment	94.7	37.6
Royalty Allowance	0.3	0.1
Preproduction Cost	7.1	2.6
Inventory & Initial Chemicals	1.6	0.3
Interest during Construction	15.7	6.2
Land	1.3	0.2
TOTAL CAPITAL REQUIREMENT	120.7	47.0

Source: Reference 7.
* Home office expenses.

R

R. I [illegible]

TABLE 2-15. LIME SPRAY DRYER/FABRIC FILTER - UTILITY SYSTEM FIRST YEAR OPERATING COSTS

Basis: **2x500 MW, New Plant**
70% Capacity Factor, 6132 hr/yr
Eastern Coal: Illinois, St. Clair
4.0% Sulfur, 1,927,000 acfm/unit
Western Coal: Wyoming, Campbell
0.48% Sulfur, 2,085,000 acfm/unit

July 1, 1978 Costs

	Unit	Unit Rate	Eastern Coal		Western Coal	
			Annual Quantity	Annual Cost	Annual Quantity	Annual Cost
		($)		($x1000)		($x1000)
Operating Labor	manhour	12.50	68,000	850	60,000	750
Maintenance Labor				1,794		1,175
Maintenance Material				2,709		1,773
Admin/Support				793		578
Total Fixed O&M Cost				6,146		4,276
Utilities						
Process Water	10^3 gal	0.40	244,000	98	236,700	95
Electricity	kWh	0.03	39×10^6	1,170	18×10^6	540
Chemicals						
Lime	ton	34.00	287,000	9,757	40,500	1,377
Other Consumables				1,000		344
Waste Disposal	ton	6.50	556,000	3,614		
	ton	10.00			81,000	810
Total Variable O&M Cost				15,639		3,166
TOTAL FIRST YEAR OPERATING COST				21,785		7,442

Source: Reference 7.

TABLE 2-16. LIME SPRAY DRYER/FABRIC FILTER - UTILITY SYSTEM 30-YEAR LEVELIZED REVENUE REQUIREMENTS

Basis: 2x500 MW, New Plant
70% Capacity Factor, 6132 hr/yr
Eastern Coal: Illinois, St. Clair
4.0% Sulfur, 1,927,000 acfm/unit
Western Coal: Wyoming, Campbell
0.48% Sulfur, 2,085,000 acfm/unit

	Levelized mills/kWh	
	Eastern Coal	Western Coal
Process Capital	1.7	0.7
General Facilities	0.2	0.1
Engineering, H.O.* Fees	0.2	0.1
Contingency	0.7	0.2
Total Plant Investment	2.8	1.1
Preproduction Inventory & Misc.	0.3	0.1
AFDC **	0.5	0.2
Total Capital Requirement	3.6	1.4
Operating & Admin Labor	0.5	0.4
Maintenance Labor & Mat.	1.4	1.0
Total Fixed O&M Cost	1.9	1.4
Utilities		
Electricity	0.4	0.2
Chemicals & Consumables	3.3	0.5
Waste Disposal	1.1	0.2
Total Variable O&M Cost	4.8	0.9
TOTAL LEVELIZED REVENUE REQUIREMENTS	10.3	3.7

Source: Reference 7.
*Home office expenses.
**AFDC = Allowance for funds during construction

TABLE 2-17. UTILITIES CONSIDERING DRY FGD FOR NEW UNITS

UTILITY	PLANT SITE	COAL TYPE	COMMENTS
Central and Southwestern Services	Coleto Creek Unit 2	0.4% S average; subbituminous	Considering only dry FGD. 9/86 scheduled start-up.
East Kentucky Power Cooperative	J.K. Smith, Units 1 and 2	NR[a]	Considering dry and wet for two 650 MWe units. 1985-1986.
Nebraska Public Power	Fossil III	0.36% S	Considering dry only for 650 MWe unit. 1987 scheduled start-up.

Source: Reference 8.

[a] NR = Not Reported.

TABLE 2-18. STATUS OF SPRAY DRYING R & D ACTIVITIES

Program	Location	System Size	Status
EPA-funded tests conducted by Cottrell Environmental Sciences, Inc.	Public Service of Colorado's Comanche Station	10,000 acfm	Test work completed in early 1981. Final report to be published in late 1982.
EPA-funded tests conducted by G.E. Environmental Services, Inc.	City of Colorado Springs' Martin Drake Station	20,000 acfm	Test work complete. Final report to be published in 1983.
EPRI-funded pilot and laboratory tests; prime contractor: Radian Corporation.	Public Service of Colorado's Arapahoe Station and Radian Corporation laboratories.	Pilot-scale: 9000 acfm Laboratory: 40 scfm	Testing in progress.
DOE tests	Pittsburgh Energy Technology Center (PETC).	2,500 acfm	Testing complete. Results reported at 1982 EPA/EPRI FGD Symposium.

EPA-funded testing at Martin Drake and the PETC work have recently focused on high sulfur coal applications. At Martin Drake, eastern fly ash was injected into the flue gas just upstream of the spray dryer and SO_2 spiking was used to raise the inlet SO_2 to between 1500 and 4000 ppmv.[2] At PETC, inlet SO_2 concentrations of about 2200 ppmv were generated by burning a 3.1 percent sulfur West Virginia coal. Over 90 percent SO_2 removal was demonstrated in both these test programs. Details on the results can be found in Section 3.12 for the Martin Drake tests and Section 3.6 for the PETC tests.

The Comanche and EPRI-funded pilot programs have been directed toward low sulfur western coal applications. Comanche tests are summarized in Section 3.3 and EPRI's program is discussed in Section 3.8.

In general, these R&D programs have indicated that the major process variables influencing SO_2 removal in the spray dryer system are:

- fresh reagent ratio,
- approach to saturation at the dryer outlet, and
- recycle ratio.

However, optimization of gas/liquid contact, atomization quality, and gas residence time in the dryer have been shown to be important not only from an SO_2 removal standpoint, but also in ensuring trouble-free spray dryer operation.

Other variables that have been shown to impact SO_2 removal in the spray drying system are:

- inlet SO_2 concentration,
- temperature drop over the spray dryer,
- slaking water quality, and
- lime reactivity.

Results from R&D programs such as the ones discussed above, combined with recent operating data from full-scale commercial systems and demonstration programs, have provided better definition of the important spray dryer FGD design and operating parameters. However, there remain a number of areas in which consistent, well-characterized data have not been published. Basically, there are five major areas of current technical interest:

- atomization,
- the role of fly ash and recycle solids,
- high sulfur coal applications,
- less expensive reagents than lime, and
- utilization schemes for solid waste.

Continued research and development in the atomization area is focused primarily on improving atomizer designs for FGD applications and comparing the performance of nozzle and rotary atomizers. Atomizer design research centers on reducing abrasion and power requirements while maintaining a finely atomized slurry. At least three vendors are investigating the use of nozzle atomizers for smaller industrial applications (e.g., less than 250,000 acfm), but would favor rotary atomizers for utility and large industrial systems. The two types of atomizers are generally compared on the following bases:

- droplet size produced,
- power requirements,
- mechanical complexity,
- spray patterns produced,
- abrasion and/or plugging experiences, and
- ability to handle slurry flows associated with varying boiler load.

Regarding the role of fly ash and recycle solids in the spray drying process, the major R&D objective is to maximize the use of available fly ash alkalinity (or acidity) and unreacted reagent in the recycle solids. Meeting this objective requires:

- a more thorough understanding of the mechanisms by which fly ash alkalinity (or acidity) contributes to SO_2 removal in systems both with and without recycle,
- conclusive data on the optimum manner in which the recycle solids are added (e.g. separate slurrying versus direct addition to the fresh reagent feed tank), and
- characterization of the potential role of fly ash as a surface catalyst in SO_2 absorption.

Some of the recent data from high sulfur coal applications such as Argonne, Strathmore, Riverside, and Martin Drake have answered previously posed questions regarding the SO_2 removal achievable at higher inlet SO_2 levels. These results have also provided some information on the reagent ratios, approach to saturation, and recycle ratios required to obtain high removals (90 percent or greater) at 2000 to 4000 ppm inlet SO_2. Research and development activities for high sulfur coal applications continue to focus on optimization of atomization, spray dryer operation, and solids recycle to reduce fresh reagent requirements. Reducing reagent requirements will be important to the relative economics of spray drying, since reagent-related costs are a major component of the annual operating costs of spray dryer systems. Figure 2-10 shows limited parametric test data indicating the reagent ratio required for between 70 and 90 percent SO_2 removal at low and high inlet SO_2 concentrations. These data show that for 90 percent SO_2 removal a 0.8 reagent ratio is required for the low sulfur case, but a reagent ratio of about 1.3 is required for the same removal in the high sulfur case. For a 500 MWe utility system, this translates into approximately 63,000 more tons of lime annually for the 2000 ppmv inlet SO_2 case than the 800 ppmv inlet SO_2 case. (These calculations are based on 90 percent SO_2 removal, 75 percent load factor, and 95 percent CaO lime.) Assuming $75/ton of lime, this is an annual cost difference of $4,725,000.

Because reagent-related costs are such a significant portion of the total operating costs for lime-based FGD systems, there is continued interest in alternate reagents such as limestone, adipic acid-enhanced lime and limestone, and possibly MgO as the basis for a regenerable spray dryer process for higher sulfur coals. Both EPA and DOE have conducted limited tests with limestone and adipic acid enchancement. SO_2 removal was less than 40 percent in all of these tests, even at a close approach to saturation. A few vendors are also investigating the use of limestone, but no data have been published.

In the waste disposal area, efforts are being directed primarily toward complete characterization of waste properties as a function of coal type and FGD process conditions and development of methods for utilization of the waste solids, possibly as road base or cement additives.

2.3 DRY INJECTION

Presently, there are no plans for the construction of any commercial dry injection systems. However, several demonstration programs have been conducted. Demonstration-scale dry injection systems have been or are being operated through funding by DOE, EPA, and the Electric Power Research Institute (EPRI). The current status of these demonstration programs is presented in Table 2-19.

General Electric Environmental Services (formerly Buell, a division of the Envirotech Corporation) completed EPA-funded dry injection testing at the City of Colorado Springs' Martin Drake Station in May 1980. Experiments with three reagents (nahcolite, raw trona, and refined trona) were conducted on the 4500 acfm dry injection baghouse system (10). The sorbents were ground to less than 74 μm in diameter before being injected into the duct leading to the fabric filter. These tests were performed in an attempt to characterize the effects of reagent type, reagent ratio, temperature, and air-to-cloth ratio on SO_2 removal. The results of these parametric tests were summarized in the Third Survey of Dry SO_2 Control Systems (EPA-600/7-81-097).

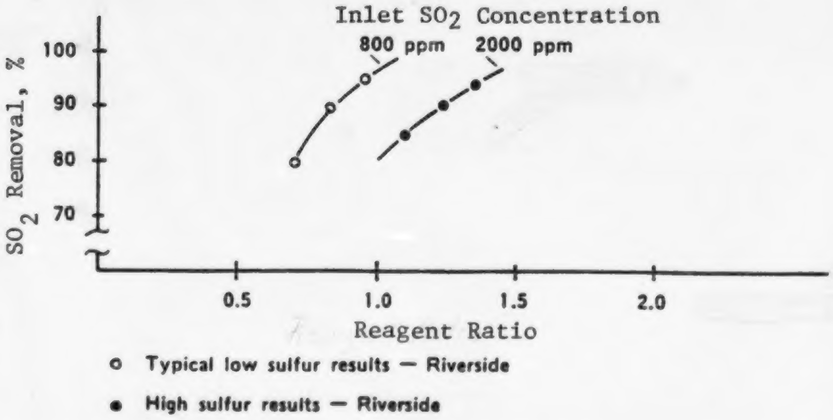


Figure 2-10. Effect of inlet SO_2 concentration - Riverside data.
Source: Reference 9.

TABLE 2-19. CURRENT DRY INJECTION PROGRAMS

Vendor	Location	Size	Comments
EPA/General Electric[a]	Colorado Springs Martin Drake Sta.	4500 acfm	Testing completed in May 1980. EPA funded.
DOE/Grand Forks Energy Technology Center	GFETC Labs	200 acfm	Testing complete. Report is being prepared.
DOE/Pittsburgh Energy Technology Center	PETC Labs	500 lb coal/hr furnace	Testing completed. Report is in preparation.
EPRI/KVB	Public Service Co. of Colorado Cameo Station	22 MWe	Testing completed. Report is in preparation.

[a] Formerly Buell-Envirotech.

The DOE has conducted research on dry injection systems at both the Grand Forks Energy Technology Center (GFETC) and Pittsburgh Energy Technology Center (PETC). These tests have been performed in order to characterize several process parameters, such as reagent type, inlet SO_2 concentration, inlet gas temperature, bag materials, and air-to-cloth ratios.

Work conducted at GFETC with a 150-scfm (nominal) dry injection system showed that up to 90 percent utilization (based on combined NO_x and SO_2 removal) could be obtained with trona and nahcolite. Moderate sulfur western coals were used in these tests, resulting in an inlet SO_2 concentration of 650 to 1100 ppmv. The results reported here are preliminary; a final report on these tests has not been published yet.

Dry injection work at the Pittsburgh Energy Technology Center (PETC) was completed in the Fall of 1980. The dry injection studies evaluated the performance of nahcolite, trona, and commercial sodium bicarbonate. The average baghouse temperature for the dry injection tests was 400°F. The fabric filter was equipped with Nomex bags and was operated at an air-to-cloth ratio of 4 ft/min. In general, nahcolite showed the greatest SO_2 removal capability of the three reagents evaluated.

In tests conducted with 1.1, 1.6, and 3.5 percent coals, dry injection of nahcolite resulted in SO_2 removals of up to 95 percent with a reagent ratio of 1.5 moles Na_2O per mole of inlet SO_2. The tests also indicated that SO_2 removal decreased as inlet SO_2 concentration increased. However, 90 percent SO_2 removal was reportedly achieved with a reagent ratio of 1.5, even when 3.5 percent sulfur coal was burned.

EPRI's Air Quality Control Program has sponsored research on the technical aspects of a dry injection/baghouse system. Detailed laboratory scale tests have been completed. The results of these tests were summarized in the Second Survey of Dry SO_2 Control Systems (EPA-600/7-71-018). EPRI has also completed large-scale dry injection tests at the Public Service of Colorado's Cameo Station. The tests were performed by KVB, Inc. on the 22 MWe Unit 1 boiler at Cameo, using the existing fabric filter. The majority of the testing was conducted with nahcolite, but some testing was conducted with trona.

The results of the Cameo dry injection tests showed that SO_2 removals of 75 to 83 percent were achievable with nahcolite at a normalized stoichiometric ratio (NSR) of 1.0 and an inlet SO_2 concentration of 450 ppm.* The effect of nahcolite NSR on SO_2 removal is shown in Figure 2-11. Other results from the Cameo dry injection tests showed that the temperature of the flue gas at the point of reagent injection had a significant effect on the rate of reaction between nahcolite and SO_2. Also, SO_2 removals of 54 percent were achieved with trona at an NSR of 0.95.

---

*The NSR is defined as moles of Na_2O fed per mole of inlet SO_2.

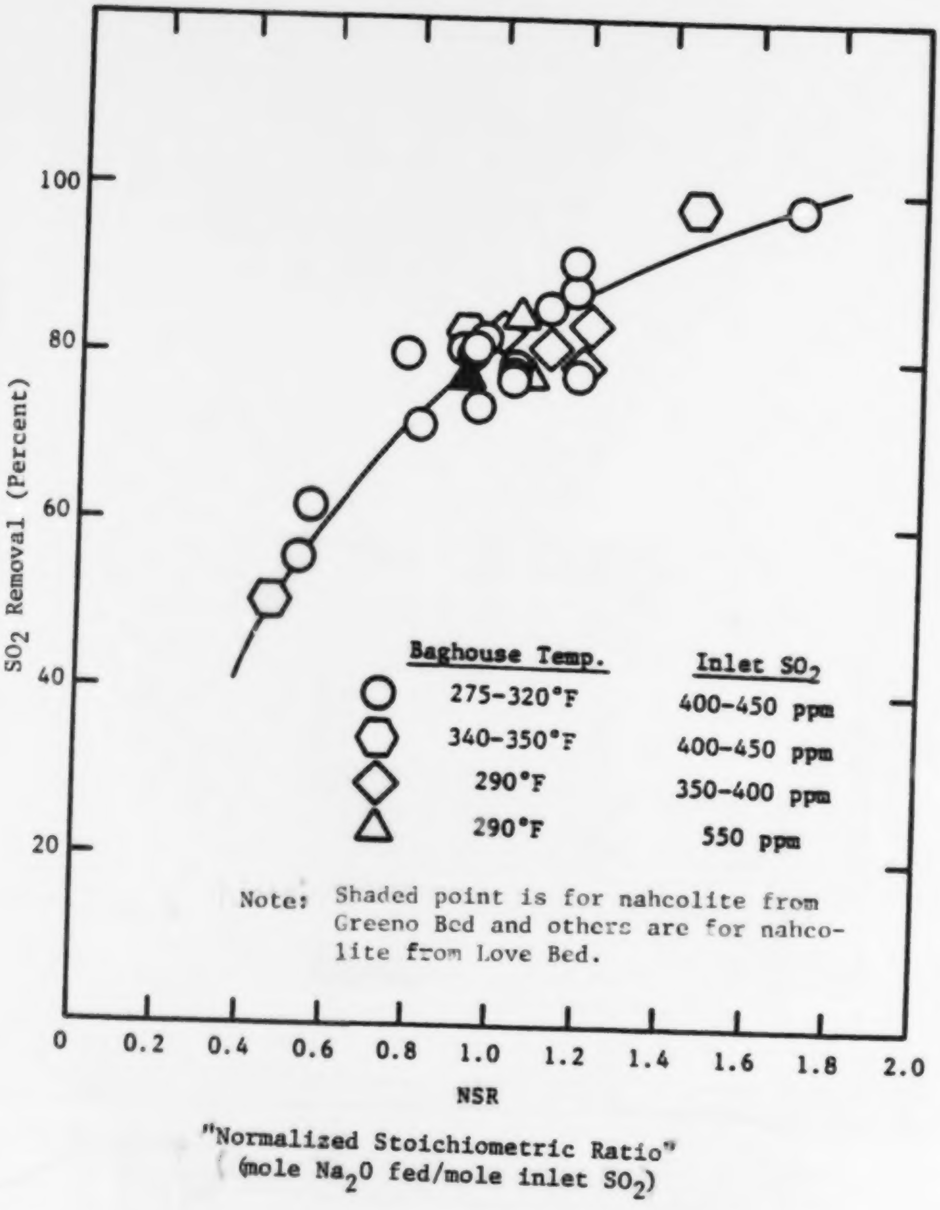


Figure 2-11. Effect of nahcolite NSR on SO_2 removal.

Source: Reference 11.

2.4 COMBUSTION OF COAL/ALKALI FUEL MIXTURES

As discussed earlier, there are two processes being developed which are based on the combustion of coal/alkali fuel mixtures to control SO_2 emissions: combustion of coal/limestone pellet in an industrial stoker-fired boiler and combustion of a pulverized coal/alkali fuel mixture in a low-NO_x burner. This second process is commonly referred to as limestone injection in a multi-stage burner, or LIMB.

Large-scale tests with a 3.5:1 calcium-to-sulfur molar ratio coal/limestone pellet were conducted in December 1979. Results of these tests indicated that 50 percent SO_2 removal was achievable with this technology. However, inadequacies in the pellet production process have resulted in a delay of full-scale testing. Under EPA funding, Battelle Columbus Laboratories is continuing to investigate alternate methods of making the pellets. Meanwhile, only small-scale, short duration tests are planned for the future.

Both the DOE and EPA are conducting studies on pulverized coal/alkali fuel mixtures. All of this work is being conducted with calcium-based reagents, and the majority is with limestone.

The EPA's program to develop coal/alkali fuel mixtures involves studies on three different wall-fired burners and one tangentially fired burner. Initial tests on a 1 million Btu/hr wall-fired burner have shown that SO_2 capture with limestone injection is highly variable, ranging from 10 to 70 percent depending on operating conditions. The tests showed that SO_2 capture was primarily affected by the average gas temperature and residence time in the burner.

Test results for a nominal 50 million Btu/hr medium tunnel (MT) burner and a nominal 100 million Btu/hr large watertube simulator (LWS) are shown in Figure 2-12. The tests were conducted on a 0.9 percent sulfur Utah coal and a 2.6 percent sulfur Indiana coal. During these tests, the limestone was either pulverized with the coal or injected with tertiary combustion air. Pulverizing the limestone with the coal showed better or equivalent SO_2 capture in all cases. For the high sulfur Indiana coal, SO_2 capture in the LWS was about 50 percent at a reagent ratio of 2.0. SO_2 capture in the LWS was lower for the low sulfur Utah coal. Data for the MT burner show similar trends with fuels, but SO_2 capture in the furnace is somewhat lower.

The DOE recently completed tests with limestone on the 53 MWe tangentially fired boiler at Otter Tail Power Company's Hoot Lake Station. [Final results of this testing were not available at the time of this report.]

Efforts to optimize SO_x and NO_x removal by the LIMB technology are underway. Incentives for the accelerated development of this technology include the potential cost savings offered by reduced equipment requirements relative to conventional wet FGD and the retrofit potential of the technology for existing boilers.

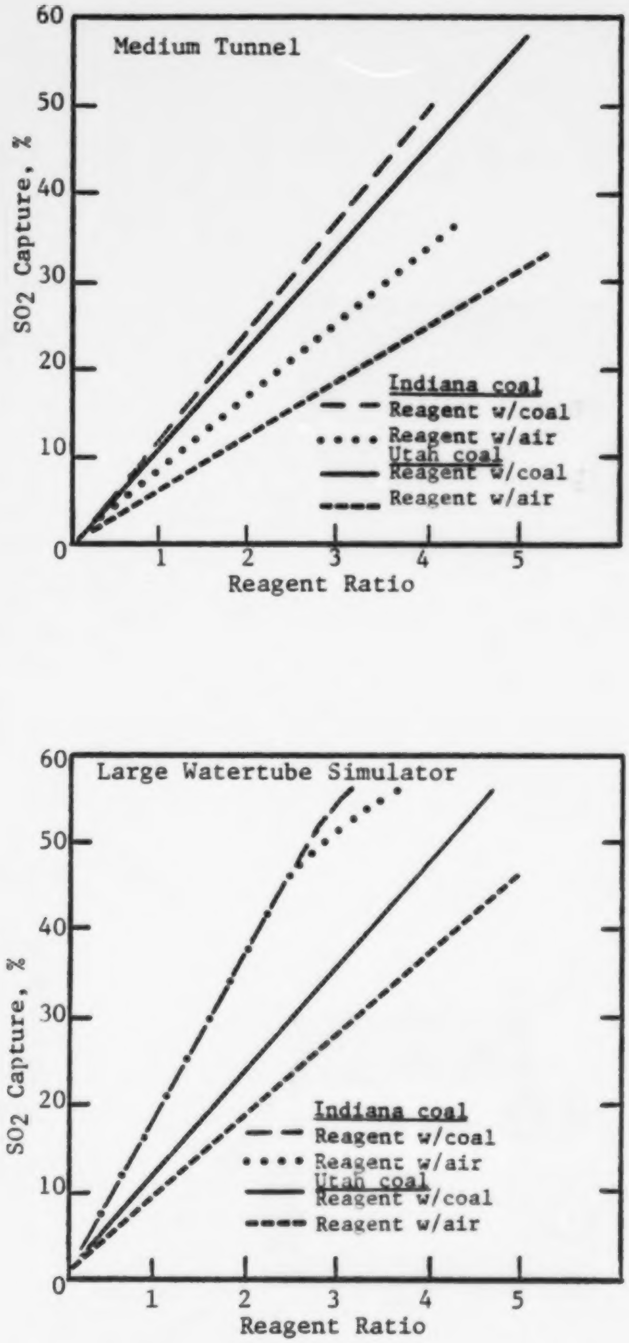


Figure 2-12. SO_2 Capture in wall-fired furnaces.
Source: Reference 12.

Figure 2-12 SO_2 Capture in wall-fired Furnaces (Reference 12.)

2.5 ELECTRON IRRADIATION SYSTEMS

The electron-beam (E-beam) process is in an early developmental state. As mentioned in Section 1.2.4, the E-beam process has not yet been applied to a real coal-fired flue gas.

The DOE has recently signed cost-sharing agreements with Research-Cottrell and Avco-Everett/EBARA to conduct pilot-scale demonstrations of E-beam processes. Research Cottrell will be developing the E-beam/lime process and Avco-Everett/EBARA is developing the E-beam/ammonia process.

2.6. REFERENCES

1. Ireland, P.A. Status of Spray Dryer Flue Gas Desulfurization. Final Report EPRI CS-2209. Electric Power Research Institute, Palo Alto, California, January 1982, 88 pp.

2. DeWolf, Glenn, et al. The Cost Digest: Cost Summaries of Selected Environmental Control Technologies. EPA Contract No. 68-02-3171. Prepared for Office of Research and Development, U.S. EPA, Washington, D.C., May 15, 1982, p. 168.

3. Farber, Paul S. "Start-up and Performance of a High Sulfur Dry Scrubber System." (Presented at the 75th Annual Meeting of the Air Pollution Control Association, New Orleans, Louisiana, June 20-25, 1982, Paper No. 82-40.5.)

4. West, Woody, Mikropul, Inc. Telephone conversation with M.A. Palazzolo, Radian Corporation, April 5, 1982.

5. Reinauer, T.V., J.P. Monat, and M. Mutsakis. "Dry FGD on an Industrial Boiler: 20,000 Hours of Operating Experience." (Presented at the 79th Annual AIChE Meeting, Cleveland, Ohio, August 29-September 1, 1982.)

6. Reference 2. pp. 220-226.

7. Bechtel National, Inc. Economic and Design Factors for Flue Gas Desulfurization Technology. Final Report EPRI CS-1428. Electric Power Research Institute, Palo Alto, California, April 1980, 180 pp.

8. Smith, M., et al. EPA Utility FGD Survey: April-June 1981. EPA-600/7-81-012d (NTIS PB 82-11 5858), U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, August 1981.

9. Felsvang, Karsten. Results of High Sulfur Operation (at Riverside Station). (Presented at the Joy/Niro Seminar, Minneapolis, Minnesota, June 26-27, 1982.)

10. Parsons, E.L., et al. "SO_2 Removal by Dry FGD." In Proceedings: Symposium on Flue Gas Desulfurization - Houston, October 1980. EPA-600/9-81-019b (NTIS PB 81-243164), April 1981, pp. 801-852.

11. Muzio, L.J., et al. "Demonstration of SO_2 Removal on a Coal-fired Boiler by Injection of Dry Sodium Compounds." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida. May 17-20.)

12. Drehmel, D.C., et al. "SO_2 Control with Limestone in Low-NO_x Systems: Development Status." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida. May 17-20.)

SECTION 3

CURRENT AND RECENTLY COMPLETED ACTIVITIES

This section reports the pertinent activities of private companies and government or other agencies involved in the development of dry FGD systems. Included here are descriptions of current and recently completed research and development activities and information on commercial systems sold or being marketed. Technical results from full-scale dry FGD operation and recent research and development programs are discussed in more detail in Section 4.

3.1 BABCOCK AND WILCOX

Address: Babcock and Wilcox
20 South Van Buren
Barberton, Ohio 44023

Babcock and Wilcox
Alliance Laboratory
P. O. Box 834
Alliance, Ohio 44601

Contact for More Information:

Tom Hurst or Cecil Miller
Fossil Power Generation Division
Barberton, Ohio
(216) 753-4511

John Doyle
Alliance Laboratories
(216) 821-9110

Background

Babcock & Wilcox (B&W) has sold two utility spray drying systems: one to Basin Electric for the utility's Laramie River Station Unit 3 and one for Colorado Ute Power Company's Craig Station Unit 3. The B&W spray dryer system is based on the use of a horizontal flow reactor equipped with "Y-jet" spray nozzles adapted from B&W's standard oil burner technology. The Laramie River system will include an ESP, rather than a fabric filter, for particulate collection. B&W favors ESPs over fabric filters for their spray drying systems. However, depending on purchaser requirements or site-specific conditions, they will substitute a fabric filter for the precipitator. In fact, the Craig Station system will have a fabric filter at Colorado Ute's request.

B&W completed a relatively large-scale (120,000 acfm spray dryer) demonstration in the Fall of 1980 at Pacific Power and Light's Jim Bridger Station. Current R&D efforts are being directed toward pilot-scale studies with high sulfur coals at their Alliance Research Center laboratories.

Research and Development

Babcock and Wilcox is currently conducting a DOE-funded program to assess the applicability of dry scrubbing to high sulfur coal-fired boilers. The two year study will involve pilot-scale testing with 2.0 to 4.5 percent sulfur coals. The studies will be conducted with a 900-scfm spray dryer/fabric filter unit located at B&W's Alliance Research Center in Ohio.

Variables to be investigated during the high sulfur coal pilot tests include spray dryer inlet temperature, approach to saturation, reagent ratio, solids recycle, air-to-cloth ratio, and fabric filter inlet temperature. Reagents other than lime will be considered, but the majority of the testing will be conducted with lime.

In one set of tests, B&W plans to inject pulverized limestone into the burner with coal and then use collected fly ash for the spray dryer slurry. Limited testing conducted by B&W with limestone injection followed by spray drying earlier this year showed that the control combination warrants further investigation. The results from the tests indicated that 90 percent SO_2 removal with combined limestone injection/dry scrubbing may be possible at a calcium-to-sulfur ratio of 3.0.

The final work planned under the DOE program is a commercial cost evaluation and comparison for a high sulfur coal-fired 500 MWe unit using dry scrubbing versus wet scrubbing.

Commercial Activities

Construction of the Laramie River system is now completed and the system is operational. No performance tests have been conducted yet due to minimal boiler needs this summer. Construction of the Craig Station system is on schedule and initial operation of the system is still expected in November 1982.

Information Sources

Miller, Cecil, Babcock and Wilcox. Telephone conversations with M. A. Palazzolo, Radian Corporation. May 30, 1982 and August 19, 1982.

Doyle, John, Babcock and Wilcox. Telephone conversation with M. A. Palazzolo, Radian Corporation. August 20, 1982.

Doyle, J. B. and B. J. Jankura. Limestone Injection with Dry Scrubbing of Exhaust Gases. (Presented at the 1982 Spring Technical Meeting of the Central States Section of the Combustion Institute, Columbus, Ohio. March 22-23, 1982.)

3.2 COMBUSTION ENGINEERING

Address: Combustion Engineering, Inc.
P. O. Box 7462-A
Birmingham, Alabama 35223

Contact for More Information: Kal W. Malki
Environmental Systems Division
(205) 967-9100

Background

Combustion Engineering (C-E) began a dry scrubbing pilot plant research and development program in February 1979 at Northern States Power Company's Sherburne County Generating Station in Becker, Minnesota. Studies with a "second generation" pilot plant were begun in October 1979 at Alabama Power Company's Gadsden Steam Plant.

Research Activities

C-E completed full parametric testing of their pilot plant at the Gadsden Steam Plant during 1981. Parameters investigated with lime included SO_2 removal efficiency as a function of: approach to saturation, liquid-to-gas ratio, reagent ratio, inlet SO_2 concentration, recycle rate, and fabric filter pressure drop.

The pilot-scale system at Gadsden has an 8-ft, 10-in diameter spray dryer that treats a slipstream flow rate of up to 10,000 acfm at 300°F. The pilot plant has two different baghouses, a pulse-jet baghouse used only to collect solid samples for analysis and a shaker type baghouse to study SO_2 removal and fabric filter performance.

The fuel burned in the Gadsden boiler is a Southern region bituminous coal with an ash content of 13 percent and a sulfur content ranging from 1.5 to 2.5 percent. C-E found that SO_2 removal with lime as the sorbent was most strongly affected by approach to saturation and liquid-to-gas ratio. C-E also reported that in their tests reagent ratio did not have a major effect on SO_2 removal in the spray dryer but did have a significant impact on SO_2 removal in the fabric filter. This result is not consistent with previous work by others that has indicated a strong dependence of spray dryer SO_2 removal on reagent ratio. C-E's tests were conducted at a 40°F approach, an inlet SO_2 concentration of 1000 to 1500 ppmv, and reagent ratios ranging from 0.6 to 1.6.

Future Activities

C-E is continuing to conduct studies at the Gadsden pilot plant. This year C-E plans to conduct additional tests with solids recycle and to test reagents other than lime. C-E is also conducting studies in the area of nozzle atomization, including studies on droplet size, gas flow patterns and models for evaporation rates and SO_2 absorption.

Commercial Activities

Although C-E has not sold any new systems, they currently have several bids outstanding on utility systems.

Information Sources

Malki, Kal, C-E. Telephone conversation with M. A. Palazzolo, Radian Corporation. May 4, 1982.

Bresowar, G. E., D. C. Borsare and K. W. Malki. "Dry Scrubber Design and Application: The C-E Approach." (Presented at the ASME/IEEE/ASCE Joint Power Generation Conference, St. Louis, Missouri, October 4-8, 1981.)

3.3 COTTRELL ENVIRONMENTAL SCIENCES/EPA

Address: Cottrell Environmental Sciences, Inc.
Air Pollution Control Division
P. O. Box 1500
Somerville, New Jersey 08876

U. S. Environmental Protection Agency
Industrial Environmental Research Labs
Research Triangle Park, North Carolina 27711

Contact for More Information:

Research - Dr. Nicholas J. Stevens
Manager, Chemical Process Development
Cottrell Environmental Sciences, Inc.
(201) 685-4887

Dr. T. G. Brna
EPA Project Officer
(919) 541-2683

Commercial - Robert Roop
Product Manager, Fabric Filter and Dry FGD
Cottrell Environmental Sciences, Inc.
(201) 685-4284

Background

Cottrell Environmental Sciences (Cottrell) has completed demonstration-scale testing at two sites: privately-funded testing at Texas Utilities Big Brown Station and EPA-funded testing at Public Service of Colorado's Comanche Station. Cottrell, in a joint venture with Komline-Sanderson, has been awarded a contract for a commercial spray drying system to serve United Power Association's Stanton Station. Komline-Sanderson supplies the spray dryer equipment and technology for the joint venture systems.

Research and Development

Results of the EPA-funded testing at Comanche have been compiled in a final report that should be released by the end of 1982. The results of a technoeconomic study comparing lime dry scrubbing with limestone wet scrubbing will also be presented in the report.

Some of the more recent results from testing at the Comanche and Big Brown are discussed below. For more details, see Information Sources at the end of this section.

During the final phase of EPA-funded testing at Comanche, Cottrell conducted a continuous 120-hr demonstration run on the 10,000 acfm Comanche spray dryer/fabric filter FGD system. The purpose of the demonstration was to verify that sufficiently high levels of SO_2 removal can be achieved on a sustained basis to meet New Source Performance Standards (NSPS) applicable to western low sulfur and lignite coals. The demonstration was successfully conducted without interruption, and SO_2 removal during the run averaged 68.8 percent compared to a target value of 70 percent. The reagent ratio ranged from 1.1 to 2.1 with an average value of 1.6, for an average reagent utilization of 43 percent. The average approach to saturation temperature was 35°F.

Inspection of the interior walls of the spray dryer following the demonstration run showed that they were very clean. However, eight of the 12 holes in the periphery of the rotary atomizer had become completely plugged and two other holes were partially plugged. The pluggage reportedly had no discernible effect on SO_2 removal during the demonstration run.

Other recent results from the Comanche and Big Brown studies relate to the relative SO_2 removal in the spray dryer and fabric filter, effects of spray dryer and fabric filter operating temperatures, fabric filter pressure drop versus SO_2 removal and product solids particle size and moisture characteristics.

During testing at Comanche and Big Brown, it was found that reagent ratio and the approach to saturation are two of the more significant parameters affecting SO_2 removal in spray dryer/fabric filter systems. Cottrell found that the relative SO_2 removal in the spray dryer compared to the fabric filter decreased as the reagent ratio increased. This is shown in Figure 3-1. The relative SO_2 removal in the spray dryer decreased at higher reagent ratio because more unreacted lime was conveyed to the fabric filter for reaction.

Figure 3-1 also shows that relative SO_2 removal in the spray dryer was significantly affected by spray dryer and fabric filter operating temperature. The relative SO_2 removal in the spray dryer is higher at lower operating temperatures and when the fabric filter temperature is higher than the spray dryer temperature (flue gas reheat).

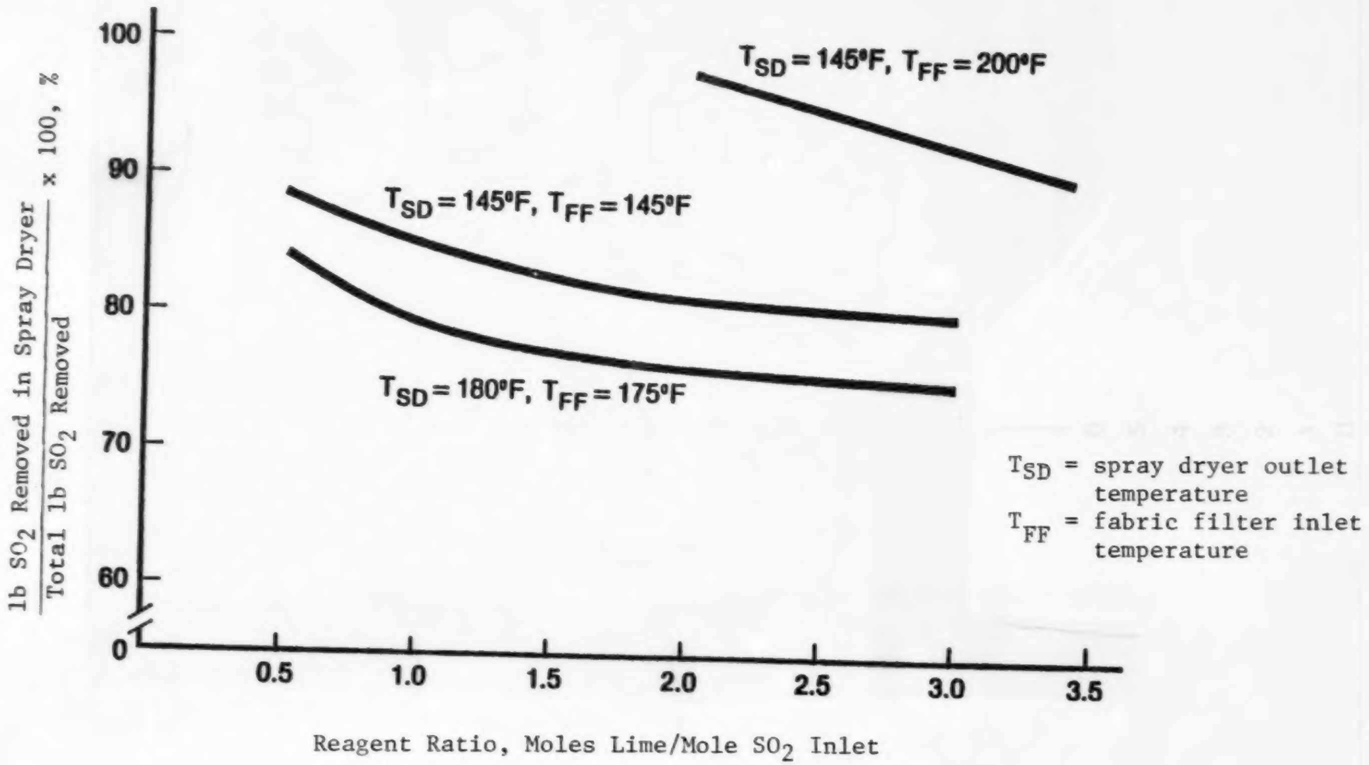
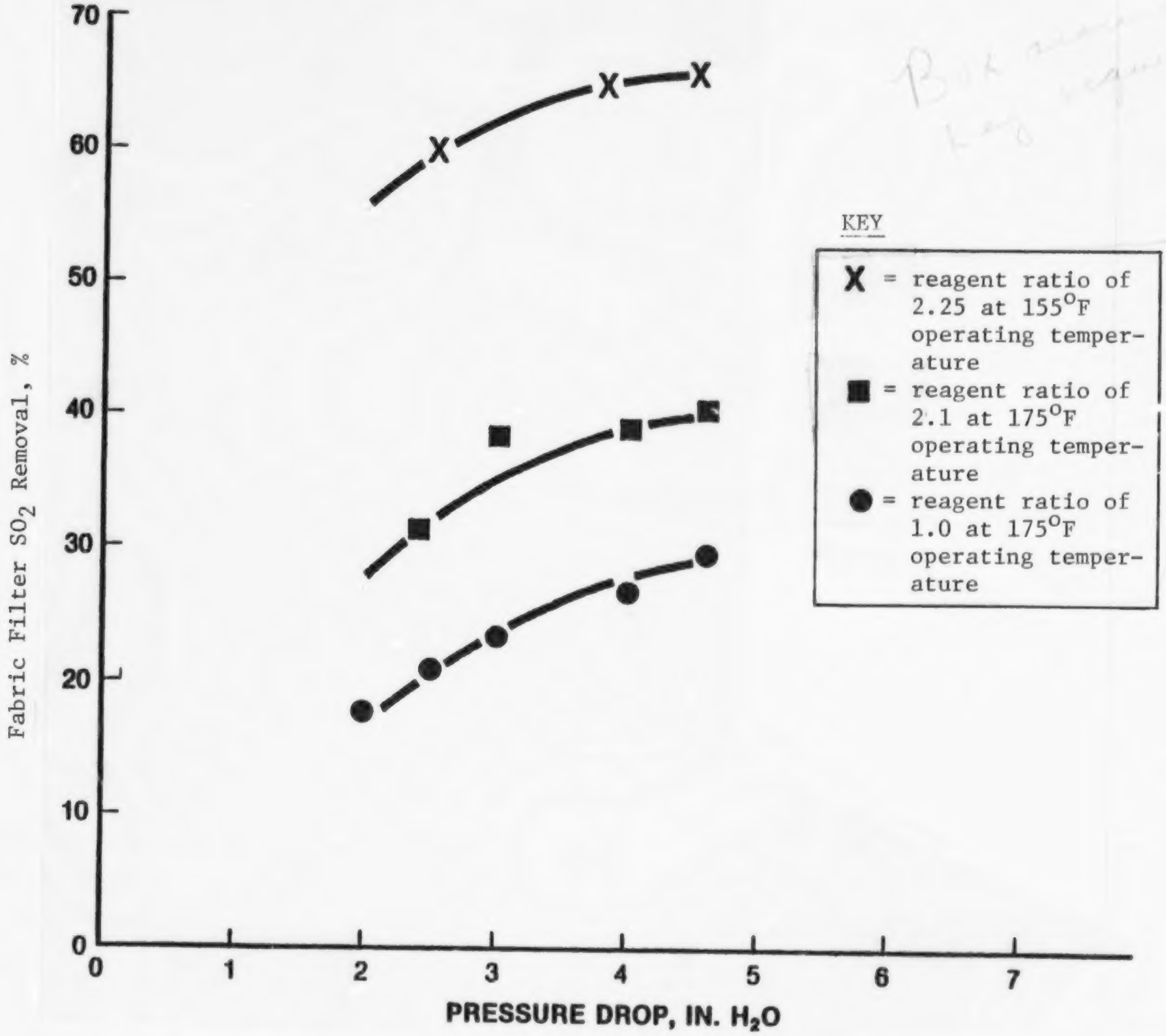


Figure 3-1. Relative SO_2 removal in spray dryer compared to fabric filter.

Source: Stevens, Nicholas, J. (See Information Sources at the end of this section.)



Box around key separately

Figure 3-2. Fabric filter SO_2 removal versus fabric filter pressure drop.

Source: Stevens, Nicholas J. (See Information Sources at the end of this section.)

The SO_2 removal across the fabric filter was found to increase with fabric filter pressure drop at three different operating conditions as shown in Figure 3-2. Figure 3-2 also shows that SO_2 removal in the fabric filter increased with increasing reagent ratio and with decreasing operating temperature.

The average particle size of product solids collected in the spray dryer hopper was found to be larger than that of solids collected at the fabric filter. The mean diameter of spray dryer solids was measured as 30-35 μm versus about 10 μm for fabric filter solids.

In tests relating to product solids moisture content, it was found that the percentage of total solids collected at the spray dryer increases directly with the moisture content of the solids. In "normal" operation, spray dryer solids were found to contain 10-25 percent water versus 5 percent for the fabric filter solids. The approach to saturation for these results was not reported. These moisture content values are significantly higher than those reported for other systems, which are generally less than 2 percent residual moisture in the spray dryer product at a 20 to 30°F approach.

Commercial Activities

Construction of the spray drying/fabric filter system as United Power Association's Station Station has now been completed. System startup was scheduled for the Fall of 1982.

Future Activities

Although Cottrell will continue to conduct in-house studies for bid preparation, no further pilot-scale studies are planned at the Comanche Station.

Research-Cottrell has recently received a contract with the Department of Energy (DOE) to conduct a 2-year pilot-scale study on an electron-beam process that employs electron irradiation and spray drying for the control of SO_x and NO_x. The DOE program is discussed in Section 3-4 below.

Information Sources

Roop, Robert, Cottrell Environmental Sciences, Inc. Telephone conversations with M. A. Palazzolo, March 10 and August 20, 1982.

Stevens, Nicholas J., et al. "Dry Scrubbing SO_2 and Particulate Control." In Proceedings: Third Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. I, EPA-600/9-82-005a, July 1982, pp. 313-322.

Stevens, N. J., et al. Dry SO_2 Scrubbing Test Program. Draft Report prepared for U.S. Environmental Protection Agency. EPA Contract No. 68-02-3190. May 1981.

3.4 DOE/AVCO-EVERETT/EBARA AND DOE/RESEARCH-COTTRELL

Address: Flue Gas Cleanup
U. S. Department of Energy
Washington, D. C. 20545

Contact for More Information: Edward G. Trexler
Program Manager
301-353-4743

Background

EBARA Corporation of Japan conducted initial work on an ammonia-based electron irradiation process in the early '70s and tested a 3 MWe pilot unit at a steel sintering plant in 1977 and 1978. EBARA later joined with Avco-Everett, a U. S. Company that has been conducting bench-scale studies since 1977.

DOE's involvement in E-beam NO_x/SO_x control began in 1979 when Research-Cottrell performed bench-scale studies on a lime-based E-beam process under a DOE contract. The E-beam process is described in Section 2.5.

Future Activities

The DOE has signed cost sharing cooperative agreements with both Research-Cottrell and Avco for pilot-scale studies of the E-beam process. The pilot systems will treat flue gas from coal-fired boilers. Sites for the pilot tests are still being negotiated.

Research-Cottrell will evaluate the E-beam/lime slurry process with a 10,000-acfm pilot plant. NO_x and SO_x removal optimization tests will be conducted at electron irradiation rates between 0.5 and 1.5 Mrad (1 Mrad is equivalent to 10 joule/g of flue gas). During the scheduled 2-year program, Research-Cottrell will also conduct nitrate fixation tests and electron-gun cost reduction studies.

Avco-Everett/EBARA will conduct 10,000 to 20,000 acfm pilot studies on the E-beam/ammonia injection process. Testing of this process is planned for a high sulfur eastern coal. Following optimization and reliability testing, Avco and EBARA plan to investigate the potential use of waste products from the process as fertilizer.

In addition to the pilot-scale studies, DOE also plans to conduct reaction kinetics studies during 1982 and 1983.

Information Sources

Trexler, Edward, Department of Energy. Telephone conversation with M. A. Palazzolo, Radian Corporation, July 28, 1982.

Trexler, Edward C. "DOE's Electron Beam Irradiation Developmental Program." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20, 1982.)

3.5 DOE/GRAND FORKS ENERGY TECHNOLOGY CENTER

Address: Grand Forks Energy Technology Center
P. O. Box 8213
University Station
Grand Forks, North Dakota 58201

Contact for More Information: Harvey Ness
Grand Forks Energy Technology Center
(701) 795-8000

Background

Grand Forks Energy Technology Center (GFETC) has conducted research on dry injection systems on a 150-scfm scale, comparing nahcolite and trona sorbents. GFETC also completed limestone injection studies at Otter Tail Power Company's Hoot Lake Station.

Research and Development

Parameters investigated on the 150-scfm dry injection system using nahcolite and trona included inlet SO_2 concentration, inlet gas temperature, bag materials, air-to-cloth ratio, and the sequencing of reagent addition and bag cleaning cycles. A final analysis of these tests had not been published at the time of this report.

GFETC has also completed sodium recovery tests. The purpose of the tests was to determine the potential for recovering unspent sodium in the spent reagent/fly ash mixture from dry injection systems. The recovery process tested involves (1) leaching spent sodium-based sorbent from FGD waste product, (2) converting the leachate to a NaCl brine and (3) producing $NaHCO_3$ using an ammonia-soda ash process technology. The results of the study indicated that the recovery process may be capable of an overall sodium yield approaching 89 percent. For more details, see Information Sources at the end of this section.

Another study recently completed by GFETC involved limestone injection studies at Otter Tail Power Company's Hoot Lake Station in Minnesota. Final results of the testing conducted on the 53 MWe tangentially fired unit were not available at the time of this report.

Current research being conducted by GFETC involves the use of a propane-fired 130-scfm burner and a new baghouse with ceramic filters. The SO_2 removal performance of calcium compounds injected into flue gas is being assessed at temperatures in the range of 1400 to 2900°F. Sulfur dioxide removal is being assessed by collecting the calcium compounds on ceramic filters in a baghouse capable of operating over a temperature range of 200 to

1000°F. Preliminary results from the testing show limestone utilizations up to 40 percent for some test conditions. GFETC plans eventually to incorporate the results of the limestone injection work with ammonia reduction of NO_x to develop a technology for simultaneous removal of SO_2, NO_x, and particulate.

Information Sources

Ness, Harvey, GFETC. Telephone conversations with M.A. Palazzolo, Radian Corporation, July 27, and October 27, 1982.

Kapsalopoulou, A. J., et al. Regeneration of FGD Dry Sorbent Materials Phase I: Final Report. DOE/FC/10179-2, U.S. Department of Energy, Grand Forks, North Dakota, May 1982.

3.6 DOE/PITTSBURGH ENERGY TECHNOLOGY CENTER

Address: Pittsburgh Energy Technology Center
4800 Forbes Road
Pittsburgh, Pennsylvania 15213

Contact for More Information: Richard Demski
Combustion Division
(412) 675-5730

Background

DOE's Pittsburgh Energy Technology Center (PETC) has conducted small pilot-scale research to evaluate both dry injection and spray drying. It is currently investigating the use of a fluidized bed of copper oxide (CuO) sorbent combined with ammonia injection for the simultaneous removal of SO_2 and NO_x. The spray drying program has focused on high sulfur eastern coal applications.

Research

During 1981, PETC conducted tests of a small pilot-scale spray dryer/fabric filter system. The system treated flue gas from a 500 lb/hr pulverized coal-fired combustion facility designed to simulate industrial water-wall boilers. A schematic diagram of the test facility is shown in Figure 3-3. The 7-ft diameter spray dryer was equipped with a 6-in. diameter rotary atomizer with three ¼-in. diameter holes. Flue gas flow to the dryer was about 2500 acfm at 400°F, resulting in a 7- to 8-second dryer residence time. The bottom-exit dryer was followed by a pulse-jet fabric filter, operated at an air-to-cloth ratio between 2.8 and 3.5 ft/min. Most tests were conducted without solids recycle. Fresh feed slurry was combined with dilution water just upstream of the atomizer. [One unusual feature of the system is air agitation of the feed slurry. This feature is not generally included in commercial system designs. It is possible that such aeration, depending on the air flow rate, could result in conversion of some $Ca(OH)_2$ to $CaCO_3$, thus reducing the $Ca(OH)_2$ available to react with SO_2 when the slurry is contacted with the flue gas. However, no chemical analyses of the feed solids after aeration were reported.]

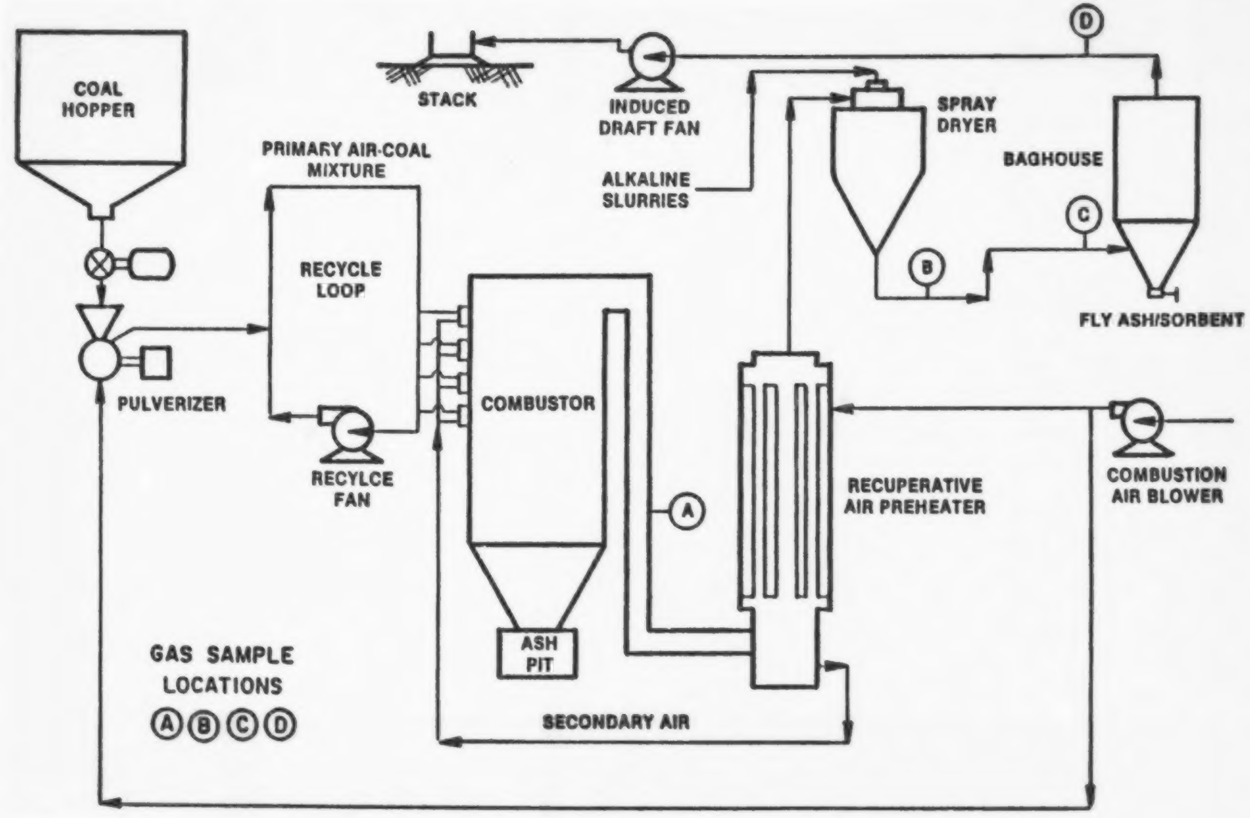

COAL HOPPER
STACK
INDUCED DRAFT FAN
SPRAY DRYER
BAGHOUSE
PRIMARY AIR-COAL MIXTURE
ALKALINE SLURRIES
RECYCLE LOOP
PULVERIZER
RECYLCE FAN
COMBUSTOR
FLY ASH/SORBENT
COMBUSTION AIR BLOWER
RECUPERATIVE AIR PREHEATER
ASH PIT
SECONDARY AIR
GAS SAMPLE LOCATIONS
Ⓐ Ⓑ Ⓒ Ⓓ

Figure 3-3. PETC pilot-scale spray dryer test facility.
Source: Yeh, J.T., et al. See Information Sources at the end of this section.

Gas composition (SO_2, CO, CO_2, NO_x, O_2, and total hydrocarbons) was continuously monitored at the fabric filter outlet. Other gas sampling and analyses points were the furnace outlet, the spray dryer outlet, and the fabric filter inlet. Moisture content of the flue gas at the spray dryer outlet was measured with a mass spectrometer.

Tests were conducted with commerical hydrated lime, lime slaked on-site, magnesium oxide, limestone, and lignite fly ash. Also, addition of adipic acid to lime and limestone slurries was investigated. The results of testing are described in detail in a paper, authored by PETC, that will be included in the 1982 EPA/EPRI FGD Symposium Proceedings (See Information Sources at the end of this section.) The major results are summarized below. During these tests, the furnace was fired with a 3.1 percent sulfur West Virginia coal with the properties listed in Table 3-1. The spray dryer inlet SO_2 concentration (at 20 percent excess air) was about 2200 ppm.

Figure 3-4 shows the results of tests conducted with slaked lime. The pulverized quicklime (94 percent CaO) was batch-slaked at a 2.8:1 water-to-lime ratio, producing a 110°F temperature rise in three to four minutes (final temperature of 185 to 190°F). Figure 3-4 shows overall system SO_2 removal as a function of reagent ratio and approach to saturation at the dryer outlet. No solids recycle was used during these tests.

Although no fabric filter operational problems occurred during the tests with a 10°F approach, operation at such a close approach is unlikely to be considered for a commercial system due to the desire to have greater margins of safety for the downstream particulate collection system. At a 20°F approach, which is the approximate design value for many commercial systems, SO_2 removal varied from about 50 percent at a 0.7 reagent ratio to about 87 percent at a reagent ratio of 1.5. Reagent ratios of 2.0 and 2.2 resulted in slightly higher removals of about 90 percent. These results are compared with other SO_2 removal data in Section 4.6.

Figure 3-5 shows the measured effect on SO_2 removal of varying atomizer speed from 15,300 to 20,300 rpm (400 to 525 ft/sec tip speed). The increase in SO_2 removal with increasing tip speed was accompanied by a corresponding decrease in spray dryer outlet temperature. The improved SO_2 removal is likely attributable to operation at a closer approach to saturation resulting from finer atomization at high speeds. Solids moisture content data were not presented for the various atomizer speeds, but it is probable that the solids formed at the lower atomizer speeds (higher outlet gas temperature) had higher moisture contents than those in the higher speed tests due to incomplete evaporation and drying. Most tests at PETC were conducted at an atomizer speed of 20,000 rpm, with a resulting tip speed of about 490 ft/sec. Typical atomizer tip speeds for commercial systems range from 500 to 600 ft/sec.

Tests with a limestone feed slurry showed only about 25 percent SO_2 removal at a 2.0 reagent ratio (20°F approach and 2200 ppm inlet SO_2). With 3000 ppm adipic acid added to the feed slurry, SO_2 removal was about 35 percent at a reagent ratio of 2.0. It should be noted that these tests were conducted in a once-through (no solids recycle) mode.

TABLE 3-1. PROPERTIES OF HIGH SULFUR EASTERN COALS USED IN PETC TESTS

Coal source: West Virginia		
Proximate analysis: (wt %, dry basis)	39.1 %	volatile matter
	50.2 %	fixed carbon
	10.7 %	ash
Ultimate analysis: (wt %, dry basis)	5.0 %	hydrogen
	74.2 %	carbon
	1.2 %	nitrogen
	3.1 %	sulfur
	5.8 %	oxygen
	10.7 %	ash
	13,378 Btu/lb	heating value
	1.0 %	moisture, as fired
Ash analysis: (wt %)	20.4 %	Al_2O_3
	7.3 %	CaO
	21.9 %	Fe_2O_3
	1.8 %	K_2O
	1.4 %	Na_2O
	45.8 %	SiO_2
	1.5 %	MgO

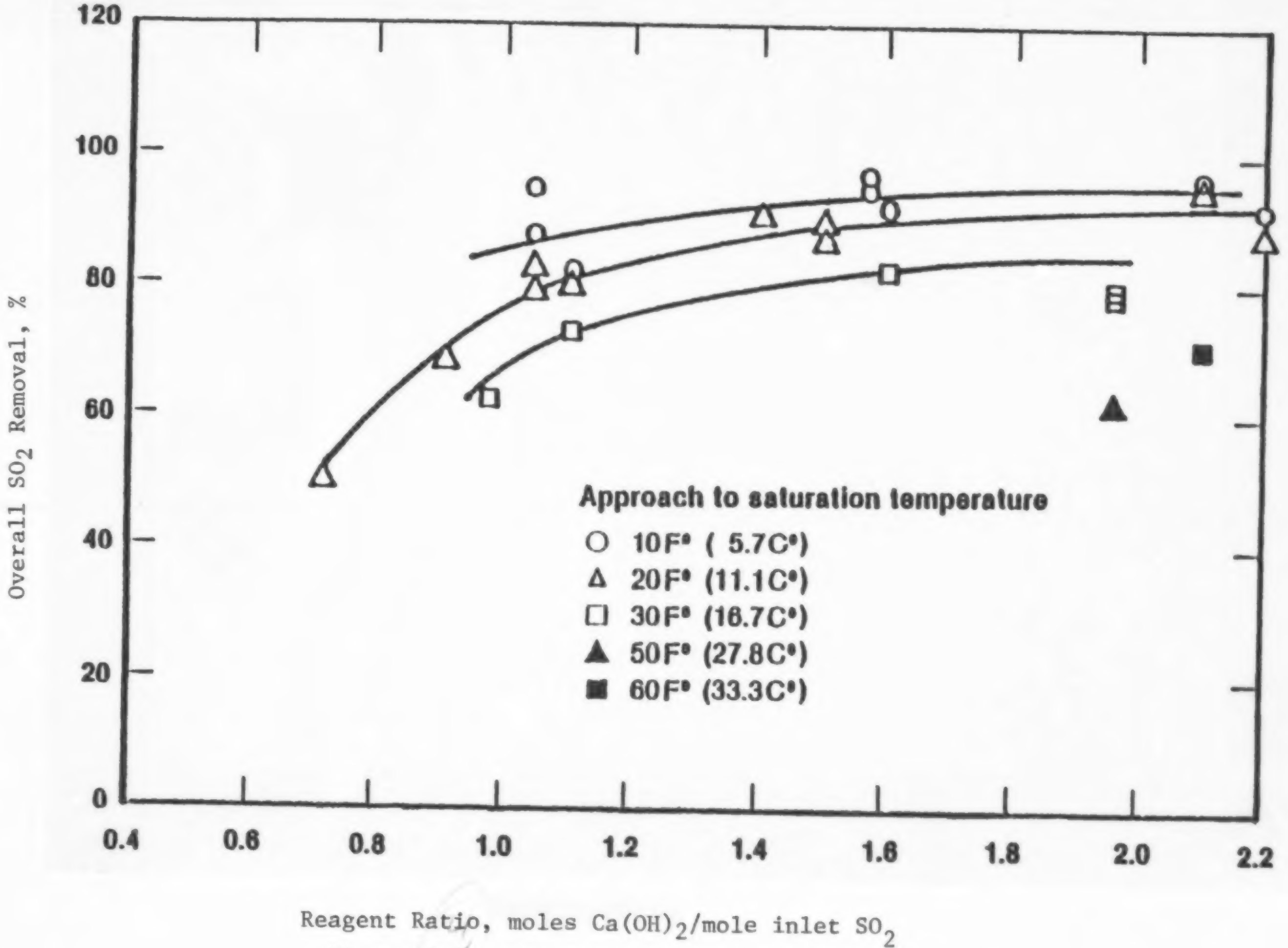


Figure 3-4. SO_2 removal with slaked lime (PETC).
Source: Yeh, J. T., et al. See Information Sources.

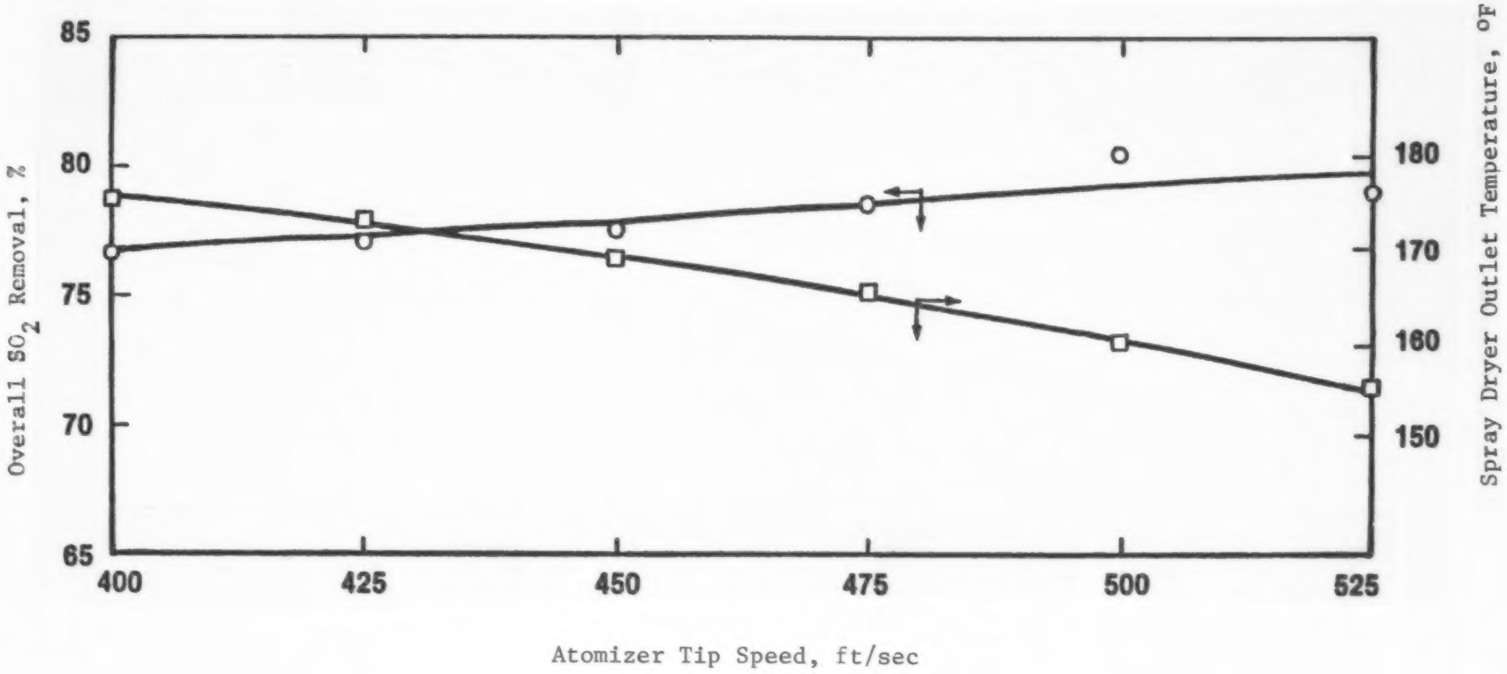


Figure 3-5. Effect of atomizer tip speed on SO_2 removal (reagent ratio = 1.0).
Source: Yeh, J. T., et al. See Information Sources.

PETC also conducted a limited number of tests using a slurry of commercial grade MgO. Results of these tests are shown in Figure 3-6. The MgO was slurried with cold water for 10 minutes before being fed to the spray dryer. The maximum overall system SO_2 removal obtained, at a 20°F approach, was 85 percent. A 2.8 MgO/inlet SO_2 reagent ratio was required to achieve this removal.

The final series of spray dryer system tests conducted by PETC examined the SO_2 removal capability of fly ash from a boiler fired with North Dakota lignite. The amount of alkaline species in the ash and results are shown in Table 3-2. These results can be compared to earlier tests conducted by Babcock and Wilcox (See Downs, W., et al., "Control of SO_2 Emissions by Dry Scrubbing." Presented to the American Power Conference, Chicago, Illinois, April 21-23, 1980). In the B&W tests, a North Dakota lignite was fired in a laboratory combustion facility. The fly ash-laden flue gas, containing less than 1000 ppm SO_2, was contacted with water in the spray dryer. An SO_2 removal (across the spray dryer and fabric filter) of about 40 percent was obtained (20°F approach to saturation). Both the PETC and B&W tests indicate that significant SO_2 removal can be obtained with highly alkaline lignite fly ash in a spray dryer system, especially if the ash is reslurried and atomized into the spray dryer.

Future Testing

All of PETC's upcoming FGD research efforts will be focused on investigating the use of a fluidized bed containing CuO sorbent combined with ammonia injection for simultaneous removal of SO_2 and NO_x. A 3.5-ft. by 4-ft. fluidized bed will treat 1300 scfm of gas from the 500 lb/hr pulverized coal-fired combustion facility.

Information Sources

Demski, Richard, Pittsburgh Energy Technology Center. Telephone conversation with M. E. Kelly, Radian Corporation, March 11, 1982.

Yeh, J. T., R. J. Demski, D. F. Gyorke, and J. I. Joubert. "Experimental Evaluation of Spray Dryer Flue Gas Desulfurization for U. S. Eastern Coals." To be included in proceedings of 1982 EPA/EPRI FGD Symposium, Hollywood, Florida. May 17-20.

3.7 ECOLAIRE

Address: Ecolaire Systems, Inc.
380 Civic Drive
Pleasant Hill, California 94523

Contact for More Information: Jim Boyer
President
(415) 676-6315

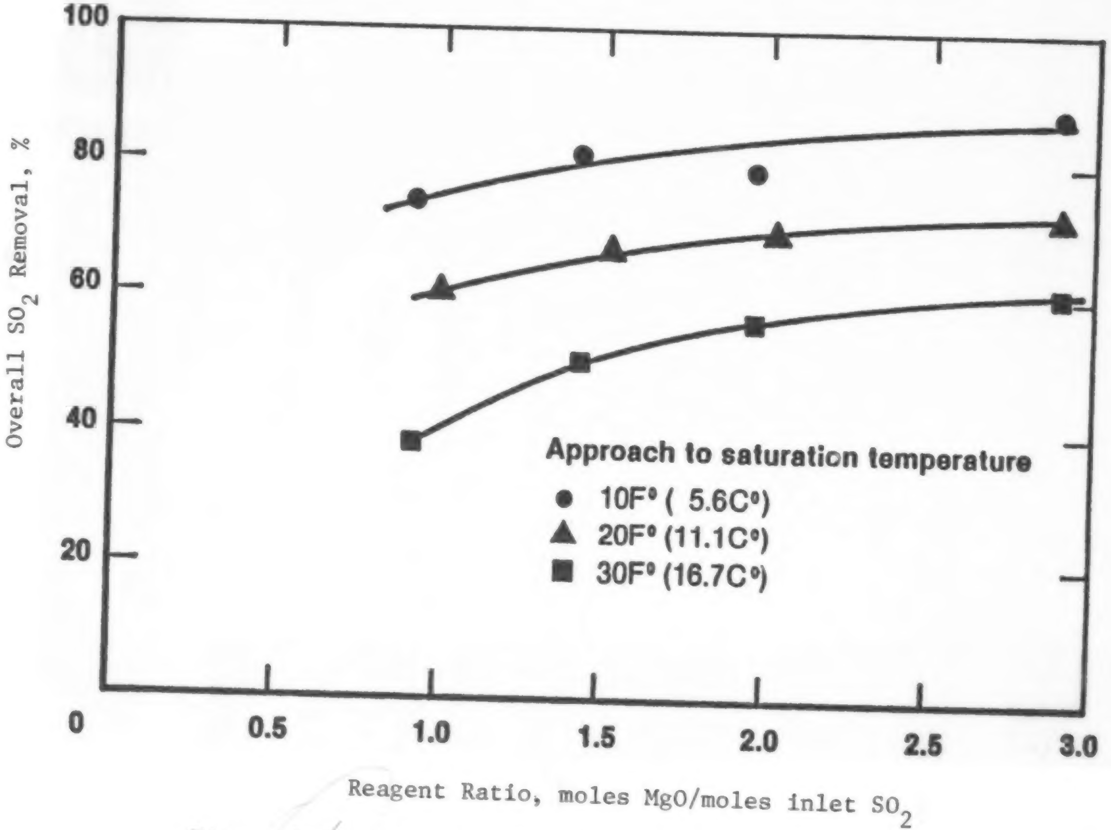


Figure 3-6. SO_2 removal with magnesium oxide.
Source: 6 Yeh, J. T., et al. See Information Sources.

TABLE 3-2. LIGNITE FLY ASH TESTS AT PETC

Ash source: North Dakota lignite

Alkaline Species Composition of Ash: (% by weight)
Ca (as CaO): 23.8%
Mg (as MgO): 6.63%
K (as K_2O): 0.36%
Na (as Na_2O): 9.04%

Test 1--Inlet SO_2: 2200 ppm (from combustion of 3.1% S West VA coal)
Ca (in ash)/SO_2 in: 1.2
(Ca + Mg + K_2 + Na_2)/SO_2 in: 2.5
Approach to saturation: 20°F
SO_2 removal: 75%

Test 2--Same conditions as Test 1, except lower inlet SO_2 (corresponding to combustion of 1% S Kentucky coal)
SO_2 removal: 71%

Background

Ecolaire has constructed a mobile pilot plant for demonstration of a spray dryer/baghouse FGD system. The unit has an Ecolaire-modified Niro atomizer spray dryer and an ICA four-section fabric filter with 12-in. diameter by 36-ft length bags. The 10,000 cfm mobile demonstration unit (MDU) is currently installed on Unit No. 1 at the Gerald Gentleman Station of the Nebraska Public Power District at Sutherland, Nebraska.

In November 1980, Ecolaire sold a commercial industrial boiler spray dryer FGD system to Container Corporation in Philadelphia, Pennsylvania.

Research and Development

Performance tests at Gerald Gentleman Station were conducted last year at inlet SO_2 concentrations ranging from 300 to 2,500 ppm. The factors studied included SO_2 removal efficiencies versus reagent utilization, temperature drop across the spray dryer, inlet SO_2 concentration, and the effects of solids recycle and boiler turndown. In addition, performance of both rotary and nozzle atomizers was evaluated. Results of the tests are considered proprietary and information on the types of tests conducted most recently is not available.

Commercial Activities

The Container Corporation system began operation in March 1982. The system recently passed performance guarantees for 90 percent SO_2 removal.

In April 1981, Ecolaire sold a spray drying system to N.C. Carbon Company, a manufacturer of calcined petroleum coke. The spray dryer treats offgases from a natural gas-fired kiln used to calcine a refinery coke feedstock. Sulfur from the coke feedstock produces 1000 to 1200 ppmv SO_2 in the 205,000 acfm (at 405°F) gas stream. The spray dryer has a design efficiency of 90 percent SO_2 removal and employs a fabric filter for solids collection.

Ecolaire currently has three outstanding bids and two other bids are being prepared.

Information Source

Horn, Richard, Ecolaire. Telephone conversation with M. A. Palazzolo, Radian Corporation, March 10, 1982.

3.8 ELECTRIC POWER RESEARCH INSTITUTE

Address: Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, California 94303

Contact for More Information:

Spray Drying/Waste Characterization Activities: Richard G. Rhudy
EPRI Project Manager
(415) 855-2421

Dry Injection Activities: Richard Hooper
EPRI Project Manager
Arapahoe Office (Denver, Colorado)
(303) 936-7281

Background

The Electric Power Research Institute's (EPRI's) Air Quality Control Program is currently conducting or has recently completed several dry FGD programs, including pilot- and laboratory-scale spray dryer testing, demonstration-scale dry injection testing, dry FGD waste product characterization studies, and a report on the status of utility commercial spray dryer FGD systems. Reports or papers on each of these programs have recently been prepared and are listed below:

1. Demonstration- and laboratory-scale spray dryer tests: Blythe, G. M., *et al*. "EPRI Spray Drying Pilot Plant Status and Results." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20.)

2. Demonstration-scale dry injection testing: Muzio, L. J., et al. "Demonstration of SO_2 Removal on a Coal-Fired Boiler by Injection of Dry Sodium Compounds." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20.)

3. Waste characterization studies: Thompson, Carol May and Richard G. Rhudy. "Characteristics of Waste Products from Dry Scrubbing Systems." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20.)

4. Utility spray drying systems: Ireland, P. A. (Stearns-Roger Engineering Corporation). *Status of Spray Dryer Flue Gas Desulfurization*. EPRI CS-2209. Electric Power Research Institute. Palo Alto, California. January 1982, 88 pp.

The status and major results of the spray drying and dry injection studies are summarized below. The results of the waste characterization studies are presented in Section 5, Waste Disposal.

The status report on utility spray drying systems, which was published in January 1982, covers the design and operating parameters of the full-scale commercial utility systems sold to date. The report also includes recommendations for future test work, several of which EPRI is pursuing in its current pilot and laboratory programs.

Research and Demonstration

EPRI, with Radian Corporation as the prime test contractor, is conducting tests with a nominal 8000-acfm spray dryer/fabric filter system located at a research facility adjacent to the Public Service of Colorado's Arapahoe Station. The results of testing, which began in March 1982 and were initially scheduled to last one year, will be used to assess the operability of lime-based spray dryer FGD systems and provide design data for typical utility installations. The primary emphasis of the test program is on low sulfur coal applications with SO_2 removal in the 70 to 90 percent range. Most of the tests will be conducted with solids recycle.

Figure 3-7 is a simplified process flow diagram for the pilot system. The 10-ft diameter spray dryer, which can accommodate either rotary or nozzle atomization, has a 5.5-ft straight side and a 50° cone bottom. The vessel has interchangeable vane rings, one for normal gas flow rates and one for low flows, and can be arranged for either bottom or side gas exit. The vessel also has a bolt-in side section which can be installed to double the volume of the dryer, thereby doubling the gas residence time. At normal flue gas rates and without the added side section, the dryer residence time is 5.0 to 5.5 seconds. The gas residence time for most commercial system designs is between 8 and 12 seconds. Most subsequent tests at Arapahoe will be conducted at a 7- to 7.5-second residence time, corresponding to a nominal flow of 4200 scfm.

The fabric filter for the pilot system is one compartment of a 10 MWe equivalent four-compartment unit which EPRI has been testing for over a year. At 8000 acfm the air-to-cloth ratio is 2.1 ft/min. The fiberglass bags can be cleaned by either reverse-air or shake/deflate methods or a combination of the two techniques. Most tests will be conducted with reverse-air cleaning.

The reagent preparation area contains a ball mill, a paste-type slaker, and a detention-type slaker. The feed slurry is fed to the atomizer with progressive cavity pumps. Just prior to the atomizer, the feed slurry is combined with dilution water metered to control the dryer outlet temperature at the desired approach to saturation. Automatic slurry feed rate control is based on the outlet SO_2 concentration. Solids can be recycled from either the spray dryer bottom catch, the fabric filter catch, or both. The system initially had horizontal rectangular tanks with two agitators for slurrying of the recycle solids. However, this system has proved inadequate due to poor mixing in the tanks. In September 1982, vertical cylindrical tanks were installed. The system will have the capability for testing three recycle configurations:

- recycle solids added directly to fresh feed tank,
- recycle solids slurried, then added to fresh feed tank, and
- recycle and feed slurries combined just upstream of the atomizer.

The recycle addition rate is based on ratio controls tied to the fresh lime feed rate.

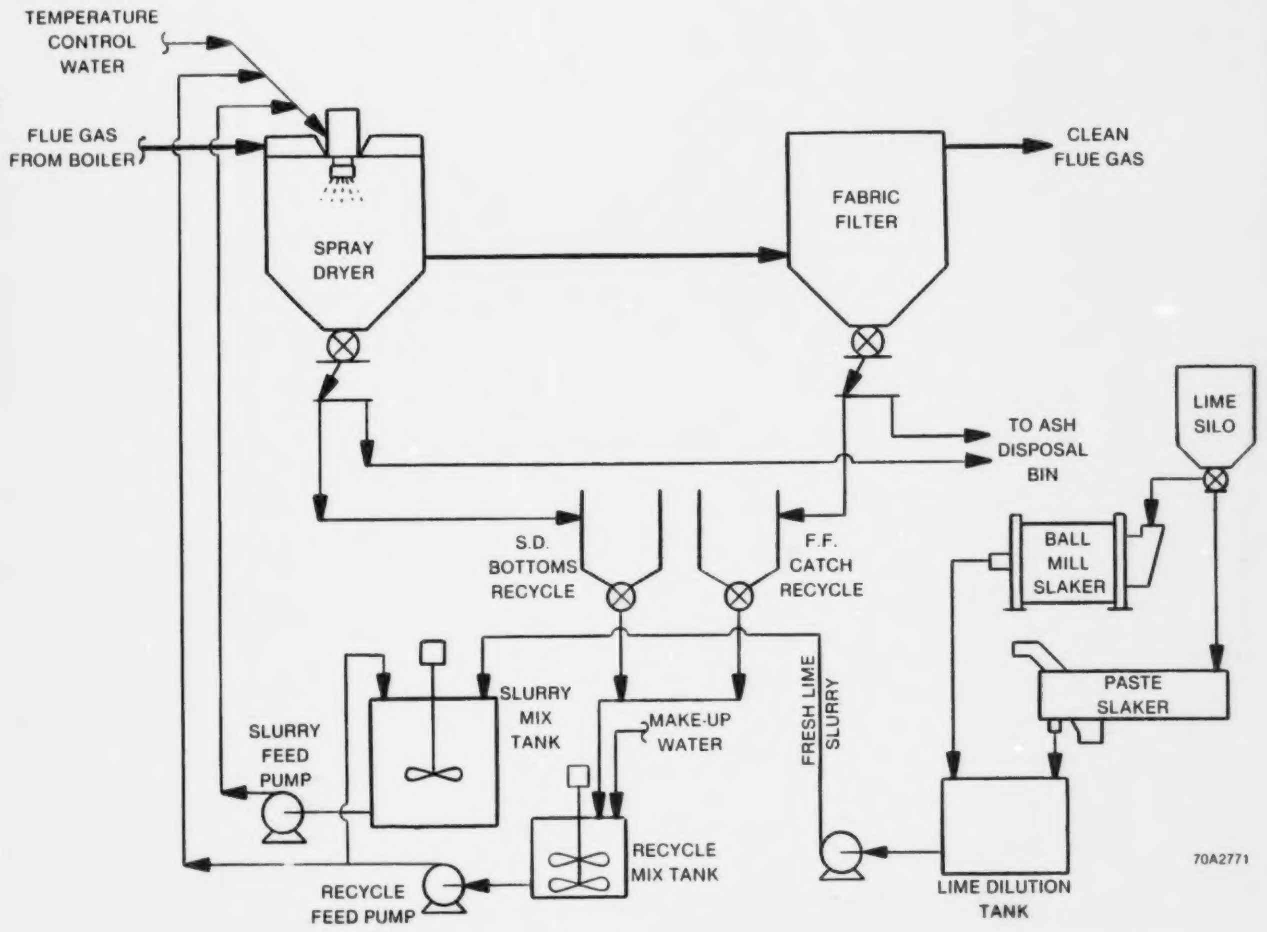

TEMPERATURE CONTROL WATER
FLUE GAS FROM BOILER
SPRAY DRYER
FABRIC FILTER
CLEAN FLUE GAS
TO ASH DISPOSAL BIN
LIME SILO
S.D. BOTTOMS RECYCLE
F.F. CATCH RECYCLE
BALL MILL SLAKER
PASTE SLAKER
SLURRY MIX TANK
MAKE-UP WATER
FRESH LIME SLURRY
SLURRY FEED PUMP
RECYCLE MIX TANK
RECYCLE FEED PUMP
LIME DILUTION TANK
70A2771

Figure 3-7. Simplified process flow diagram for spray dryer pilot plant (rotary atomizer configuration).

During the initial startup of the pilot system, problems were encountered with plugging of the holes in the rotary atomizer disk and with incomplete drying of the solids. These problems basically centered on (1) operation at gas flow rates and inlet SO_2 concentrations on the low end of the design value range and (2) too many holes (nozzles) in the atomizer wheel.

Six weeks of 100-hr duration tests in the once-through lime mode, combined with limited parametric testing, were completed in June 1982. These tests provided data on the "optimum" atomizer speed, dryer residence time and approach to saturation from an operability standpoint. Atomizer wheels with six and three holes, compared with the original 12-hole wheel, were used. Only the three-hole has since provided satisfactory atomization during operation at a 30°F approach to saturation.

Recycle testing began in July, but no published results are available at this time. The parameters to be varied during the recycle tests are fresh reagent ratio, recycle ratio, flue gas flow rate, the method in which recycle is added, the source of the recycle solids (spray dryer catch, fabric filter catch, or a mixture), and further parametric testing under recycle conditions.

Due to the initial design and startup problems, testing may continue beyond the scheduled 1-year period. Future tests will examine several aspects of the process including the effects of the spray dryer on fabric filter operation and the effects of fabric filter cleaning parameters on SO_2 removal, the use of two-fluid nozzle atomizers, the effects of increasing inlet SO_2 concentration, the effect of various slaking conditions on SO_2 removal, the use of cooling tower blowdown for dilution and/or slaking water, and, possibly, the use of alternative reagents.

In conjunction with the Arapahoe pilot program, EPRI is sponsoring laboratory-scale spray dryer testing. Radian Corporation is also the test contractor for these investigations.

A 31-in diameter 40-scfm spray dryer, equipped with an air-driven rotary atomizer and manufactured by Niro Atomizer, Inc., has been installed at Radian's Austin laboratory facilities. The dryer, which includes an ID fan and an electric air heater, has been modified for SO_2 and CO_2 spiking and continuous SO_2 monitoring of the inlet and outlet gas streams. Figure 3-8 is a schematic diagram of the test apparatus. The reagent and recycle slurries or dilution water are fed to the atomizer by small peristaltic pumps with variable speed control. The dilution water addition rate is varied to obtain the desired approach to saturation at the dryer outlet, while the percent solids in the fresh feed slurry is varied to obtain the desired ratio of fresh reagent to inlet SO_2. The slurry feed rate is measured by mass difference. Inlet and outlet gas temperatures are monitored both with dryer instrumentation and auxiliary thermocouples installed in the ducts. The rate of SO_2 addition is metered through a calibrated rotameter. Desulfurization product solids formed in the dryer are collected in a cyclone at the dryer outlet. During recycle tests, a portion of the solids are recycled by either (1) adding them directly to the fresh feed slurry, (2) slurrying the recycle solids separately, or (3) putting the recycle solids into a wet ball mill overnight and then adding them to the fresh feed slurry.

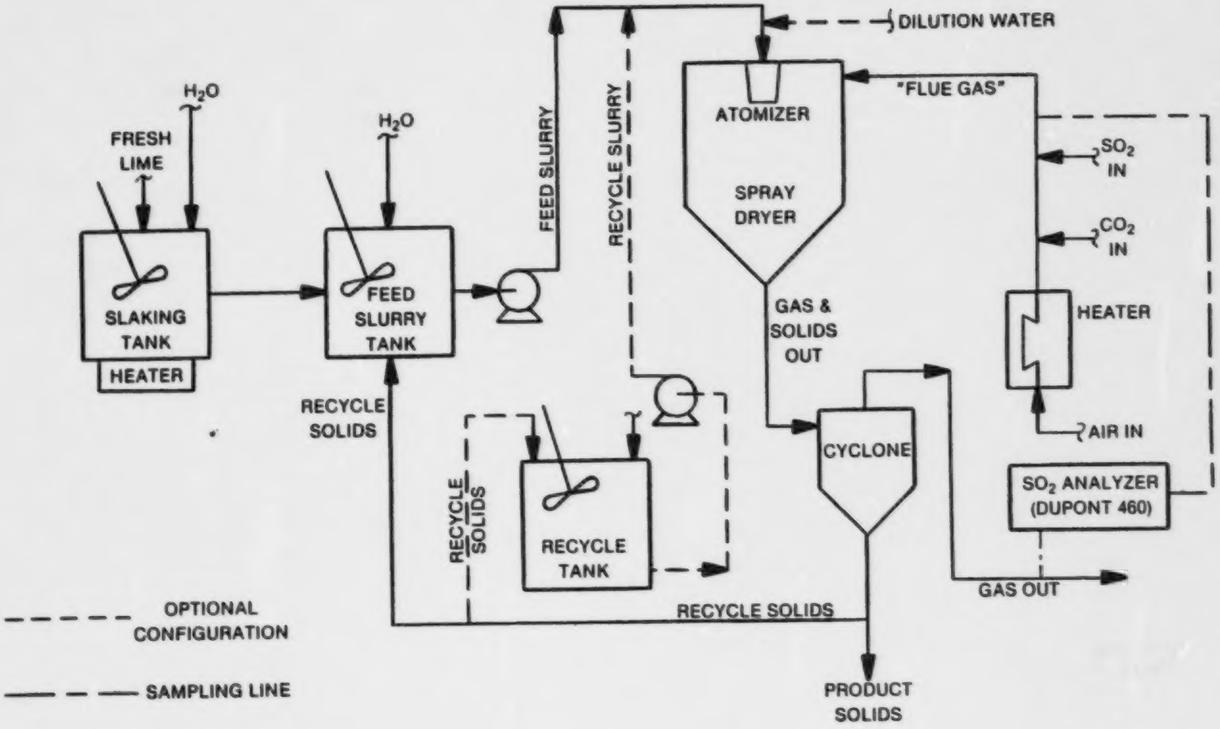

DILUTION WATER
"FLUE GAS"
ATOMIZER
SPRAY DRYER
SO_2 IN
CO_2 IN
HEATER
AIR IN
SO_2 ANALYZER (DUPONT 460)
GAS & SOLIDS OUT
CYCLONE
GAS OUT
PRODUCT SOLIDS
RECYCLE SOLIDS
FEED SLURRY
RECYCLE SLURRY
H_2O
FRESH LIME
SLAKING TANK
HEATER
H_2O
FEED SLURRY TANK
RECYCLE SOLIDS
RECYCLE SOLIDS
RECYCLE TANK
OPTIONAL CONFIGURATION
SAMPLING LINE

Figure 3-8. Schematic diagram of laboratory spray dryer system.

Although the test apparatus does have some important limitations, primarily in the fact that heated ambient air is used instead of flue gas, the advantages and flexibility of conducting preliminary test work and investigating relative effects on a system of this size are thought to outweigh the disadvantages.

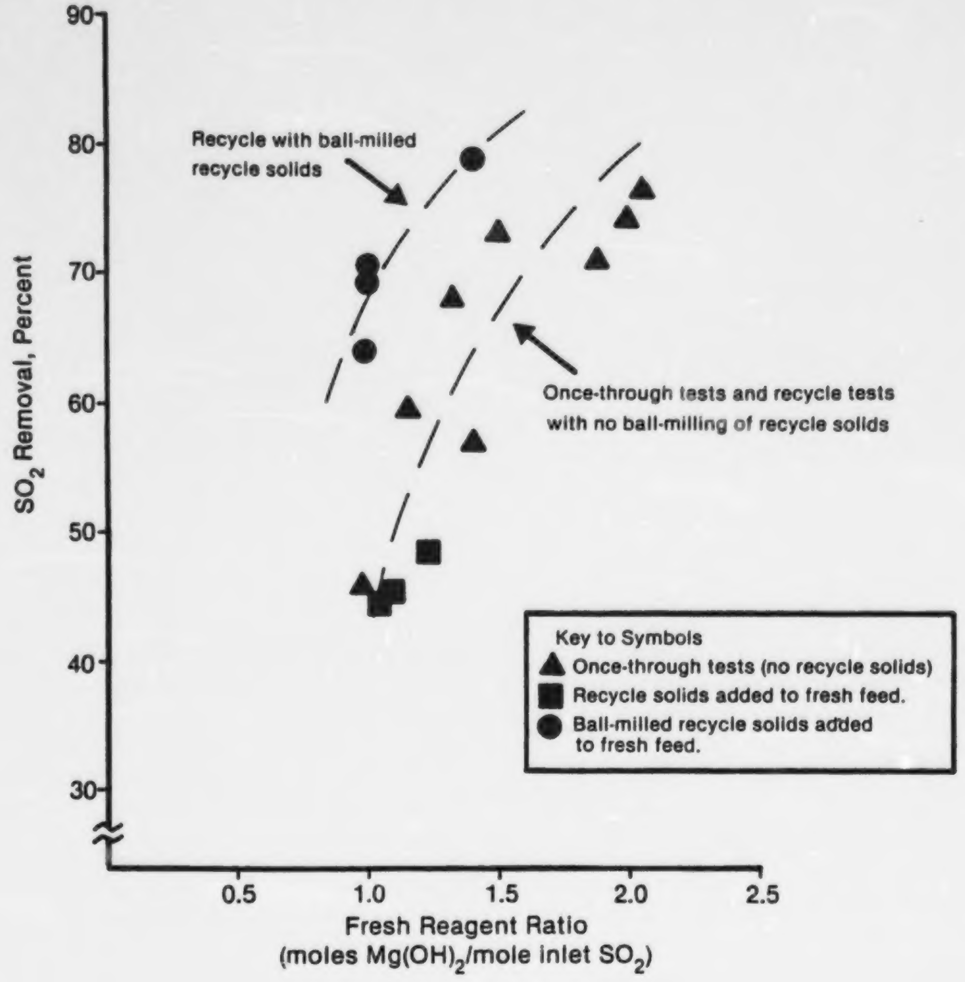
Results of baseline tests with slaked lime on a once-through basis have been reported to show relatively good agreement with previously published results from other small-scale spray dryer systems.

Because the dryer uses heated ambient air, the adiabatic saturation temperature at the dryer outlet is about 20 to 25°F lower than normal sea level flue gas adiabatic saturation temperatures. Thus, the temperature drop over the spray dryer (ΔT_{SD}) for a given approach to saturation (ΔT_{AS}) is greater than would be expected in actual field applications. A number of pilot-scale tests have shown that SO_2 removal in the spray dryer increases somewhat with an increased ΔT_{SD} (for a given ΔT_{AS}). However, these tests have also shown that operation at a relatively close T_{AS} has significantly more effect on the SO_2 removal than increased ΔT_{SD}.

Radian completed tests using various MgO reagents for SO_2 absorption in March 1982. The results were presented at the 1982 EPA/EPRI FGD Symposium in May. Major results of the MgO testing are summarized below. Tests using cooling tower blowdown as dilution and slaking water were conducted in April. The effects of fly ash in the recycle solids on SO_2 removal and lime utilization were investigated during June. Results of the last two series are currently being evaluated by Radian and EPRI. Future testing during the last few months of 1982 will be conducted in support of the Arapahoe pilot plant activities.

In the completed MgO series, several different types and grades of MgO were evaluated with respect to SO_2 removal in the spray dryer on a once-through basis. MgO calcined from $MgCO_3$ in a laboratory furnace showed better SO_2 removal than commercial MgO or $Mg(OH)_2$. Removal with the calcined $MgCO_3$ was comparable to that obtained with lime (once-through basis, 20°F ΔT_{AS}, 2600 ppm inlet SO_2). Figure 3-9 shows the results of recycle testing. No improvement in SO_2 removal relative to once-through was observed during recycle operation unless the recycle solids were ball-milled before being added to the feed slurry. At a fresh reagent ratio of about 1, SO_2 removal was improved from about 45 to 70 percent when ball-milled recycle solids were added to the feed slurry. The best SO_2 removal obtained was about 80 percent (0.75 recycle ratio, 1.5 fresh reagent ratio, 2500 ppm inlet SO_2, and 20°F ΔT_{AS}).

Radian and EPRI concluded that the test results indicated some potential for developing a regenerable MgO-based spray dryer FGD process. However, to be commercially applicable, such a process would likely have to be capable of achieving at least 90 percent SO_2 removal on a high sulfur coal. The following recommendations toward development of a commercially applicable process resulted from the test work:



Test Conditions
Inlet SO_2 ; 2500ppm
ΔTas : 14-22°F
Tin : 295-313°F
Tout : 116-124°F
Recycle Ratio : 0.5 to 0.75 $\frac{\text{lb recycle solids}}{\text{lb fresh MgO}}$

Note — curves are hand-drawn

Reagent: $MgCO_3$ calcined to MgO, slaked to $Mg(OH)_2$ for 4hrs at 190°F.

Figure 3-9. Results of MgO recycle tests.

[illegible]

#~~10~~9

- Tests should be run at higher reagent ratios and higher recycle ratios with the goal of 90 percent SO_2 removal.

- Different MgO sources and methods of fresh reagent and recycle solids preparation should be investigated since both of these aspects appear to have a significant effect on achievable SO_2 removal.

- Development and evaluation of conceptual process designs, considering such factors as the effects of fly ash in a regenerable system, optimum conditions and methods for regenerating MgO, and possible schemes for removal of $MgCl_2$ from the regenerated sorbent, should be pursued.

- The contribution of a fabric filter particulate collection device on overall SO_2 removal for an MgO-based system should be evaluated.

The results of a full-scale dry injection demonstration conducted by KVB, Inc. for EPRI at Public Service Company of Colorado's Cameo Station were also presented at the 1982 EPA/EPRI FGD Symposium. The Cameo Station consists of a 22 MWe coal-fired boiler with an eight-compartment reverse-air fabric filter. The majority of the testing was conducted with nahcolite, but some tests were made with trona.

Important results from the testing include the following:

- SO_2 removals of 75 to 83 percent were demonstrated with nahcolite at a normalized stoichiometric ratio (NSR) of 1.0 and an inlet SO_2 concentration of approximately 450 ppm. (NSR = mole Na_2O fed/mole inlet SO_2.)

- The temperature of the flue gas at the point of nahcolite injection has a significant effect on the rate of reaction between nahcolite and SO_2. Removal of SO_2 was limited to about 40 percent at an NSR of 1.0 when the gas temperature in the fabric filter dropped to 270°F.

- Poor SO_2 removal resulting from low fabric filter inlet gas temperatures was alleviated by injecting the nahcolite into a higher temperature region in the air preheater.

- SO_2 removals of only 54 percent were achieved with trona at an NSR of 0.95.

KVB reported that nahcolite injection increased the rate of change in flange-to-flange fabric filter pressure drop by about 20 percent (0.6 in. w.g./hr compared to 0.5 in. w.g./hr with fly ash only). No "appreciable" change in total pressure drop across the fabric filter was observed due to nahcolite injection.

Information Sources

(Papers listed above under Background.)

3.9 EPA-ALKALI INJECTION ACTIVITIES (LIMB)

Address: U.S. Environmental Protection Agency
Industrial Environmental Research Laboratory
Research Triangle Park, North Carolina 27711

Contact for More Information: Blair Martin
EPA Project Director
(919) 541-7504

Background

Energy and Environmental Research Corporation (EERC) conducted an EPA-funded preliminary feasibility study as part of a program to test EPA's concept of alkali injection into a low-NO_x burner for SO_2 removal. In this process, the alkali (usually limestone) is mixed and pulverized with coal prior to combustion and fired through a low-NO_x burner. Sulfur contained in the fuel reacts with the alkali present to form calcium-or sodium-based salts which are collected with the fly ash emitted from the boiler.

As a result of the favorable performance data from the initial tests, EPA in early 1981 began a fairly extensive program to study the control of SO_2 and NO_x through alkali injection into low-NO_x burners. The process is often referred to as limestone injection in a multi-stage burner, or LIMB.

Research and Development

Studies are currently being conducted on three different furnace types: wall-fired, tangentially fired, and stoker-fired. The wall-fired furnace studies are being conducted with four different furnaces at EERC laboratories in El Toro, California. The tangentially fired studies are being conducted by Acurex Corporation in Mountain View, California and the stoker-fired tests are being conducted by the University of Utah in Salt Lake City, Utah.

In addition to the test programs being conducted on the different furnace types, EPA is also funding a systems analysis study to determine the potential impacts of limestone injection on individual boiler related components (i.e., furnace, economizer, air preheater, etc.) and downstream emission control equipment. This study is being performed by Radian Corporation.

The testing being performed on each of the different furnace types is discussed below. Wall-fired furnace tests are discussed first, followed by the tangentially fired and stoker-fired furnace tests.

Wall-fired boiler studies are currently being conducted with four different wall-fired furnaces, including the following:

- a bench-scale boiler simulator furnace (BSF) with a 1 million Btu/hr firing rate,
- a small watertube simulator (SWS) with a 10 to 15 million Btu/hr firing rate,

- a medium tunnel (MT) furnace with a 30 to 80 million Btu/hr firing rate, and
- a large watertube simulator (LWS) with a 70-150 million Btu/hr firing rate.

The first phase of testing with the BSF was recently completed. The goals of this phase of the program were (1) to complete a screening study of variables affecting combustion and the time/temperature profile within the furnace and (2) to assess the effect of limestone and coal type on sulfur capture. The BSF is designed to simulate the time/temperature environment in a full-scale utility boiler and has a subscale low-NO_x distributed-mixing burner that can be operated as a conventional burner, an internally staged low-NO_x burner, or an externally staged low-NO_x burner. Preliminary results from the testing showed that SO_2 capture with limestone is highly variable, ranging from 10 to 70 percent depending on operating conditions. Capture of SO_2 was primarily affected by the average gas temperature and residence time in the burner. No results are currently available on the effect of limestone and coal types.

Preliminary test results on the LWS and MT furnaces were obtained for three different coals. The coal types included low sulfur Utah (0.9% S), moderate sulfur Indiana (2.6% S), and low sulfur German Saar Black (0.9% S). During these tests, limestone was either pulverized with the coal or injected with the tertiary combustion air. Results of tests with the Indiana and Utah coals are shown in Figure 3-10. In all cases, pulverizing the limestone with the coal showed better or equivalent SO_2 capture relative to tertiary air injection. For the Indiana coal, SO_2 capture in the LWS was about 50 percent at a reagent ratio of 2.0. SO_2 capture in the LWS was lower for the low sulfur Utah coal. Data for the MT burner show similar trends with fuels, but SO_2 capture in the furnace was somewhat lower than for the LWS.

Tangentially fired boiler studies are being conducted on a furnace with a firing rate of 1 to 3 million Btu/hr. The furnace is designed to simulate actual boiler time/temperature profiles. Testing of the tangentially-fired pilot furnace is only just getting underway, and no results are available at this time. Planned studies include the evaluation of five different calcium-based sorbents including three calcites, one dolomite, and a chalk. Three bituminous coals and one lignite coal with sulfur contents ranging from 0.6 to 3.5 percent will be tested.

In addition to studies on wall-fired and tangentially fired burners, three furnaces are being used to conduct fundamental research on sulfur capture in stoker-fired boilers. One of the furnaces is a spreader stoker that fires from 340,000 to 680,000 Btu/hr. The other two furnaces simulate the zone above the grate (or the suspension zone) and the zone on the grate (or the fixed-bed zone). Tests have been conducted on the suspension zone and fixed-bed zone furnaces with five different coals. Nitrogen and sulfur contents in the coals ranged from 1 to 1.5 percent and 0.6 to 4.0 percent, respectively.

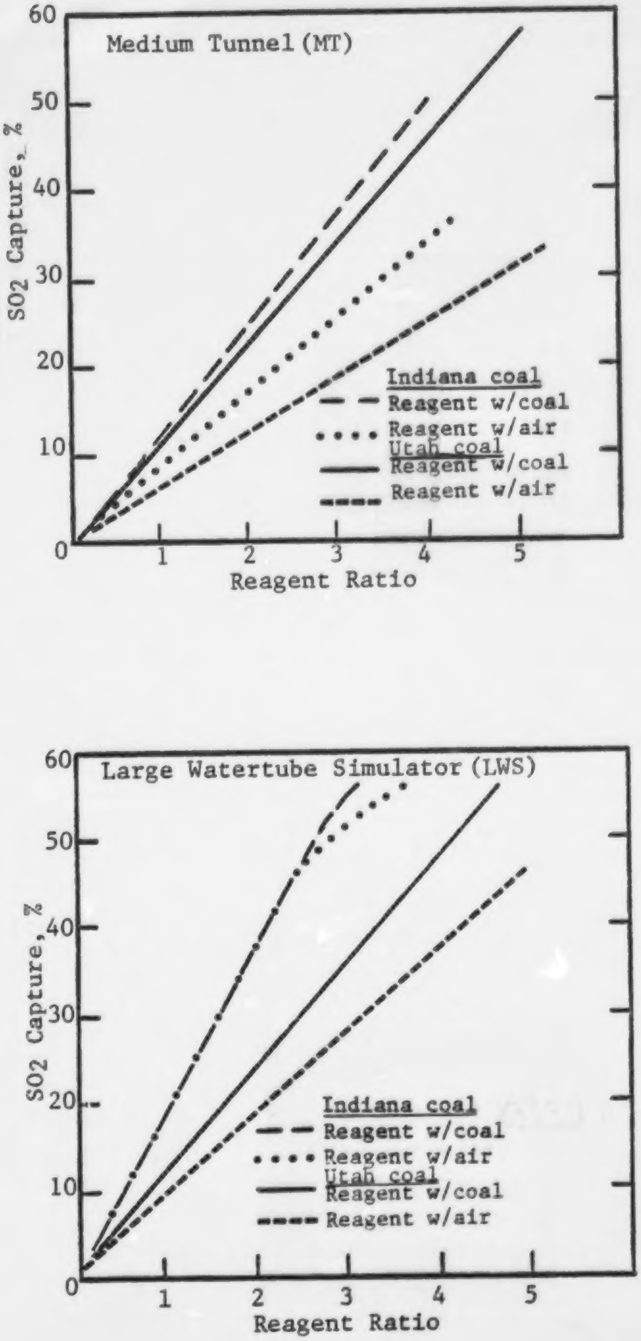


Figure 3-10. SO_2 capture in wall-fired furnaces.

10

Source: Drehmel, D. C., G. B. Martin, and J. H. Abbott. (See Information Sources at the end of this section.)

In some of these tests, coal/limestone pellets containing enough limestone to give a Ca/S ratio of 3.5 were burned. These tests showed SO_2 capture ranging from 60 percent for fuel-lean operation to 80 percent for fuel-rich (staged air) operation.

Other tests being conducted on the suspension furnace involved determining the sulfur species coming from the coal under low and high excess air conditions. Preliminary results indicate that even under low excess air, or reducing conditions, the sulfur is evolved as SO_2 and not H_2S.

Future Research

EPA's R&D plans primarily include continued efforts to optimize the LIMB technology through pilot-scale studies and fundamental research. Specific research planned for the near future includes:

- a study of reagent chemical reactions,
- pilot-scale development of LIMB processes,
- an evaluation on utility-scale low-NO_x burners,
- prototype testing of LIMB low-NO_x burners, and
- an engineering process analysis of LIMB/low-NO_x burner applications.

Information Sources

Martin, G. B., EPA. Telephone conversation with M. A. Palazzolo, Radian Corporation, August 19, 1982.

Drehmel, D. C., EPA. Telephone conversation with M. A. Palazzolo, Radian Corporation, August 23, 1982.

Drehmel, D. C., G. B. Martin, and J. H. Abbott. "SO_2 Control with Limestone in Low NO_x Systems: Development Status." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida. May 17-20.)

Brna, T. G. and G. B. Martin. "New Developments: Dry Flue Gas Desulfurization and Combined SO_x and NO_x Removal." (Presented at the Third E.C.E. Conference on Desulfurization of Fuels and Combustion Gases, Salzburg, Austria, May 18-22, 1981.)

3.10 ETS, INC.

Address: ETS, Inc.
Suite C-103
3140 Chaparral Dr., SW
Roanoke, Virginia 24018-4394

Contact for More Information: John Mycock
Vice President
(703) 774-8999

Background

ETS, Inc. has purchased all rights to the dry FGD reactor patented by Grant Hollett, Jr., Energy and Pollution Control, Inc. (EPC). This dry FGD reactor uses a hydraulically driven "slinger" to distribute dry hydrated lime into the flue gas. The reactor is followed by a fabric filter for collection of the product solids.

Commercial Activities

In May 1980, EPC ran a program of on-site pilot-scale tests for a customer in the brick manufacturing industry. A preliminary design for a commercial-sized system was submitted to the brick manufacturer, but the system was not purchased because of a downturn in the brick manufacturer's business. Meanwhile, ETS is continuing to concentrate its marketing efforts entirely on industrial applications.

Future Activities

Later this year, ETS plans to conduct parametric testing on their 200-scfm pilot unit located at the Kerr-Renfrew finishing plant in South Carolina. The site has a 60,000 lb steam/hr industrial boiler that burns low sulfur coal (0.5-0.7 percent S). Parametric tests to be conducted include determining SO_2 removal efficiency as a function of reagent ratio and inlet SO_2 concentration. Inlet SO_2 concentrations will range from 400 to 1000 ppm. In addition to SO_2 removal, the NO_x removal capabilities of the slinger reactor may also be investigated. Later testing will include tests on higher sulfur coal; no testing with solids recycle is planned at this time.

Information Source

Mycock, John, ETS, Inc. Telephone conversation with M. A. Palazzolo, Radian Corporation, May 5, 1982.

3.11 FLAKT, INC.

Address: Flakt, Inc.
1500 East Putnam Avenue
Old Greenwich, Connecticut 06870

Contact for More Information: James Farrington
Product Manager
Gas Absorption Systems
(203) 637-5401

Background

Flakt's capabilities in the dry FGD area are based on experience in four allied technologies: conditioning towers and atomization, dust collection, wet FGD processes, and dry adsorption. With the experience gained from these allied technologies, Flakt initiated its dry FGD development program in 1978.

Flakt has had three pilot-plant programs; one in Denmark, one in Sweden, and one at Pacific Power and Light's Jim Bridger Station. Studies with the Jim Bridger pilot-plant have been completed and a 100 MWe system (spray dryer used with an existing ESP) is now in place at the Jim Bridger Station.

Research and Development

Since completion of the Jim Bridger pilot studies, Flakt has constructed a 100 MW demonstration unit at the Jim Bridger Station. The unit has been purchased by Pacific Power and Light, but will be operated by Flakt during a 1-year demonstration program that began with system startup in February 1982. Flakt has already conducted performance tests on the system with both soda ash and lime reagents. Soda ash is being considered for use in the spray dryer because the reagent can be purchased fairly cheaply from a soda ash plant located 40 miles from the utility.

The results of performance tests conducted in April and May 1982 are shown in the table below.

TABLE 3-3. PERFORMANCE TEST RESULTS - FLAKT

	Soda Ash	Lime (Recycle)	Lime (No Recycle)
Gas Flow (acfm)	295,000	328,000	299,000
Inlet Temperature (°F)	224	229	238
Outlet Temperature (°F)	131	137	139
Approach Temperature (°F)	21	27	29
Reagent Ratio	1.9	2.2	1.1
SO_2 Removal (%)			
Guarantee	86.5	74	62
Actual	88.3	90.8	64.1

These tests were conducted on a 0.6 percent S coal. Following completion of the tests, the FGD system was operated to maintain an outlet SO_2 emission of 0.3 lb/10^6 Btu, which is the applicable compliance limit. This was achieved at reagent ratios of 1.15 for sodium and "less than 1.3" for lime.

The Jim Bridger demonstration unit uses an existing ESP for particulate collection. Studies to be conducted on the unit include the impacts of the different reagents on SO_2 removal in the ESP and the performance of two different types of ash conveying systems. The physical and chemical properties of the FGD wastes (leachability, compressibility, etc.) will also be investigated. Problems experienced during the startup of the Jim Bridger demonstration unit and the solutions to these startup problems are discussed in Section 4.

In tests on their pilot plant in Sweden, Flakt found that pre-collection of fly ash with a cyclone can have a significant effect on reagent requirements. Without fly ash pre-collection, 95 percent SO_2 removal was achieved at a reagent ratio of 1.9. However, with fly ash pre-collection, 95 percent removal was achieved at a stoichiometry of 1.3. These tests were conducted on a gas stream with an SO_2 concentration of 800 ppm. Fly ash pre-collection is beneficial in Sweden because the ash can be sold as a additive for cement. Other research conducted in Denmark and Sweden included studies with different reagents, such as different types of limestone and lime, and the effects of various additives on SO_2 removal.

Commercial Activities

In addition to the Jim Bridger system, Flakt has recently sold two other dry FGD systems, one in the United States and another to a utility in Malmo, Sweden. In May 1982, Flakt sold a spray dryer/ESP dry FGD system to the Grand River Dam Authority's (State of Oklahoma) station near Pryor, Oklahoma. The system will handle 1,850,000 acfm (at 250 to 300°F) of flue gas from a 520 MWe plant. Initial operation is scheduled in August 1985. The coal to be burned at the Grand River plant will range in sulfur content from 0.4 to 1.5 percent. The SO_2 removal guarantee is 85 percent and the system will employ both solids recycle and warm gas bypass. Design and operating parameters for the Grand River system are summarized in Table 3-4.

Early this year Flakt, Inc. acquired Kennecott Corporation's Carborundum Environmental Systems. With Carborundum, Flakt also acquired the sale of two 40 MWe systems being installed at the University of Minnesota. The two systems are expected to be operational at the end of 1982.

Information Sources

Farrington, James, Flakt, Inc. Telephone conversation with M. A. Palazzolo, Radian Corporation, March 10, 1982.

Rogers, Ron, Flakt, Inc. Telephone conversation with M. A. Palazzolo, Radian Corporation, August 24, 1982.

Flakt, Inc., Environmental Systems Division. Dry FGD Installation (bulletin). Flakt, Inc., Knoxville, Tennessee. 1982.

Letter and attachments from James Farrington, Flakt, Inc. to M. A. Palazzolo, Radian Corporation. Jim Bridger Project Dry FGD Demonstration Unit Startup and Testing Status Report. August 16, 1982.

3.12 GENERAL ELECTRIC ENVIRONMENTAL SERVICES, INC.

Address: General Electric Environmental Services, Inc.
200 North Seventh Street
Lebanon, Pennsylvania 17042

TABLE 3-4. DESIGN AND OPERATING PARAMETERS FOR SPRAY DRYER/ FABRIC FILTER SYSTEM AT STATE OF OKLAHOMA, GRAND RIVER DAM AUTHORITY

Design Features

- Four spray dryers (one spare) with three rotary atomizers each.
- Two dual-chambered electrostatic precipitators with five fields each.
- Warm gas bypass and solids recycle capabilities.

Design Operating Parameters

Coal properties:	0.4-1.5 percent sulfur 7% ash 8000-9600 Btu/lb
Inlet SO_2 loading:	430-1150 ppmv
Outlet SO_2 loading:	65-175 ppmv
SO_2 removal guarantee:	85%
Inlet gas flow rate:	1,850,000 acfm
Inlet gas temperature:	250-300°F

Sources: Flakt, Inc., Environmental Systems Division. Dry FGD Installation (Bulletin). Flakt, Inc, Knoxville, Tennessee. 1982.

Rogers, Ron, Flakt, Inc. Telephone conversation with M. A. Palazzolo, Radian Corporation, August 24, 1982.

Contact for More Information:

Research Projects -
Dr. T. G. Brna
EPA Project Officer
Industrial Environmental Research Labs
Research Triangle Park, NC 27711
(919) 541-2683

Dr. Eric A. Samuel
General Electric
(717) 274-7048

Commercial Activities - Mr. Bruce Galli
General Electric
(717) 272-2001

Background

General Electric (formerly Buell Emission Control, a division of Envirotech Corporation) and the Danish spray dryer firm of Anhydro A/S are currently marketing dry FGD systems in a joint venture. In Fall 1980, the G.E./Anhydro joint venture sold a dry FGD system to the Marquette (Michigan) Board of Light and Power. The system will serve the 44 MWe boiler at the utility's Shiras Municipal Power Plant.

During the past few years, G.E./Anhydro has conducted EPA-funded dry injection and spray drying demonstration testing at the City of Colorado Springs' Martin Drake Station. The dry injection work was started in October 1979 and completed in 1980. The spray dryer/fabric filter tests began in early 1980 and were completed in June 1981. Test results of both programs have been published in various papers and are being compiled in final reports that should be released in 1983. The latest test results were presented at the recent EPA/EPRI FGD Symposium in May 1982.

Research and Development

Recent work with the Martin Drake pilot plant involved performance tests under simulated high sulfur coal conditions. The Martin Drake unit normally treated an 8500-acfm slipstream containing 300 to 600 ppmv SO_2 and about 1.8 gr/ft^3 fly ash generated from combustion of a 0.4 to 0.6 percent sulfur Colorado bituminous coal. To simulate eastern high sulfur coal conditions, fly ash from three different boiler types burning high sulfur coal was injected into the flue gas slipstream. Fly ash from stoker-fired, tangentially-fired, and cyclone-fired boilers was typically injected at rates of 2.5, 2.0 and 1.0 gr/ft^3, respectively. Analyses of the high sulfur eastern coals and the Colorado coal are presented in Table 3-5.

In addition to the fly ash, SO_2 was injected into the flue gas slipstream to give inlet SO_2 concentrations in the range of 1000 to 4000 ppm. This range of inlet concentrations is typical of flue gas from boilers burning eastern coals with sulfur contents ranging from 1.5 to 5 percent.

Parametric tests conducted under high sulfur coal conditions were conducted in two phases. First, tests were performed to measure the effect of the high sulfur coal fly ash on SO_2 removal when varying the reagent ratio,

TABLE 3-5. ANALYSES OF HIGH SULFUR EASTERN BITUMINOUS COALS AND COLORADO BITUMINOUS COALS

		Composition, percent by mass			
Constituent	Boiler type:	Stoker[a]	Tangential[b]	Cyclone[c]	Front-fired[d]
Moisture		7.43	9.86	11.65	13.46
Volatile Matter[e]		38.83	35.97	35.83	41.21
Ash[e]		9.54	13.86	15.83	7.17
Fixed Carbon[e]		51.63	50.17	48.34	51.59
Sulfur		3.03	4.77	4.46	0.53
Carbon		72.17	64.41	61.86	70.54
Hydrogen		5.19	4.47	4.36	5.15
Nitrogen		1.30	1.05	0.99	1.54
Oxygen		8.77	11.44	12.50	15.04
Heating Btu/lb		13,097	11,399	11,049	12,285

[a] Stoker-fired boiler at the University of Iowa.

[b] Tangentially fired boilers in Units 5 and 6 of the Conesville Station operated by Columbus and Southern Ohio Electric.

[c] Cyclone-fired boiler in Unit 2 of the Conesville Station operated by Columbus and Southern Ohio Electric (inlet hopper sample).

[d] Front-fired boiler in Unit 6 of the Martin Drake Station operated by the City of Colorado Springs.

[e] Dry basis.

Source: Samuel, E. A., et al. See Information Sources at the end of this section.

solids recycle ratio, and inlet SO_2 concentration. Secondly, tests were conducted to provide data that would facilitate understanding of the mechanisms by which the eastern coal fly ash affects SO_2 removal. The second series of tests was conducted under the following varied conditions:

- feeding only water to the atomizer,
- feeding a slurry of fly ash and water (no lime) to the atomizer,
- reheating gas at the outlet of the spray dryer with bypass gas to increase the baghouse inlet temperature,
- varying high sulfur coal fly ash injection rates, and
- separately feeding slurries of spray dryer hopper catch and fabric hopper catch to the atomizer with lime.

All of the above tests were conducted with and without wet recycle except the water only tests. Major results of the tests conducted at Martin Drake are discussed in Section 4. The results generally showed improved SO_2 removal performance with the high sulfur coal fly ash compared to earlier results with Martin Drake fly ash only, particularly in the case of wet recycle. Efforts to determine the mechanisms by which the fly ash enhances SO_2 removal are still ongoing.

In conjunction with efforts to understand spray drying mechanisms, General Electric is currently working to provide a description of the kinetics of SO_2 removal by dry injection of nahcolite and trona. The description will involve using a fixed-bed, plug-flow reactor model to explain SO_2 removal rates for batch dry injection.

Future Research

The pilot unit operated by General Electric at the Martin Drake Station has been dismantled. Other than in-house projects relating to system controls and atomizer drive systems, General Electric is not currently planning any additional pilot-scale studies. The company is, however, planning to conduct studies on high sulfur coals on a demonstration scale. General Electric is currently looking for a site to conduct these studies. General Electric also plans to demonstrate improvements in control system applications and atomizer drive systems at the Shiras Station in the first quarter of 1983.

Commercial Activities

Construction of the 44 MWe (Shiras Station) system in Marquette, MI is completed and the system is scheduled for startup October 1, 1982. The spray dryer/fabric filter system will treat 226,000 acfm of flue gas from a pulverized coal-fired boiler burning a maximum 1.5 percent sulfur subbituminous coal.

In the area of dry injection, General Electric feels the technology is most suitable for industrial process operations, such as coke calcining and waste incineration. They feel dry injection technology is less applicable to coal-fired boilers because of economic considerations and higher SO_2 removal requirements. Dry injection may become a viable control alternative for coal-fired power plants in the western or midwestern states if low sulfur coal is fired, if land is available for sodium-based FGD waste disposal, and if the plant is close to economical nahcolite or trona sources.

Information Sources

Galli, Bruce, General Electric Environmental Services. Telephone conversation with M. A. Palazzolo, Radian Corporation, March 19, 1982.

Samuel, Eric A., et al. "Dry FGD Pilot Plant Results: Lime Spray Absorption for High Sulfur Coal and Dry Injection of Sodium Compounds for Low Sulfur Coal." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20, 1982.)

Stevens, John. General Electric Environmental Services. Telephone Conversation with M. A. Palazzolo, Radian Corporation, September 2, 1982.

3.13 JOY/NIRO

Address: Joy Industrial Equipment Company
Western Precipitation Division
4565 Colorado Boulevard
Los Angeles, California 90039

Niro Atomizer, Inc.
9165 Rumsey Road
Columbia, Maryland 21045

Contact for More Information: Jim Meyler
Consultant, FGD Systems
Joy/Western Precipitation Division
(213) 240-2300

Steven Kaplan
Sales Manager, FGD Systems
Niro Atomizer
(301) 997-8700

Background

Joy Industrial Equipment Co., through its Western Precipitation Division, and Niro Atomizer, Inc., a Copenhagen-based firm, design and supply spray drying FGD systems for both the utility and industrial boiler markets. Joy supplies the particulate collection and reagent preparation equipment. Niro provides the spray dryer and atomizer. Joy takes the lead in utility system commercial applications while Niro takes the lead in industrial work.

Joy/Niro has conducted pilot- and demonstration-scale development programs and the team has been awarded contracts for nine utility commercial spray drying systems and four industrial systems (one of which is applied to carbon regeneration furnace). In addition Joy/Niro operated a 110 MWe system at Northern States Power Company's Riverside Station for nine months in 1981 and is currently conducting a second test series scheduled to be completed late 1982. After the test program is complete, Northern States Power will operate the entire FGD system (spray dryer and fabric filter).

The research and development and commercial activities of the Joy/Niro team are discussed below. The Riverside demonstration results are also discussed in more detail in Section 4 - Technical Results, where they are compared with data from other spray drying FGD systems.

Research and Development

Joy/Niro conducts the bulk of their basic research work using a 5000-acfm pilot system located at Niro's Copenhagen facilities. This system is also used extensively to gather site-specific data required to prepare bids for commerical systems. Joy/Niro has emphasized in the past that site-specific factors such as coal and fly ash characteristics are important enough in bid preparation and system design to warrant pilot-scale testing of the process with the specific coal that will be used. Coal and ash characteristics can significantly impact fresh reagent requirements and are also likely to be a major factor in the design and operation of the fabric filter or ESP.

Joy/Niro operated the 110 MWe demonstration system at the Riverside Station for nine months in 1981, conducting both parametric and demonstration tests. A description of the Riverside system is contained in papers presented to both the 1982 American Power Conference and the 1982 EPA/EPRI FGD Symposium. Briefly, however, the spray dryer/fabric filter system has been retrofitted to treat flue gas from two existing boilers. Flue gas is diverted from ahead of the existing ESP's, and, after passing through the spray dryer, the gas can go to either the new reverse-air fabric filter or be returned to the existing precipitators. Lime for the system is slaked in either a ball mill or an attrition slaker. The spray dryer, which can treat a maximum gas flow of 680,000 acfm of flue gas at 350°F, has a roof gas disperser, a central gas disperser, and operates with a single rotary atomizer. The design gas flow is a nominal 500,000 acfm, providing a 10-second dryer residence time. A portion of the total product solids from both the spray dryer bottoms catch and the fabric filter catch are recycled by direct addition to the feed slurry tank. The Riverside system is normally operated with 35 to 40 percent solids in the slurry fed to the atomizer. Depending on the fresh lime requirements, the amount of recycle is varied to obtain the desired total percent solids in the feed slurry. (The use of recycle, and its apparent benefits with regard to system operability and possible reduction of fresh lime requirements, is discussed further in Section 4.) Dilution (temperature control) water is added just upstream of the atomizer.

Parametric tests with low sulfur fuel were conducted during March and April of 1981. The low sulfur fuel was a blend of low sulfur Colstrip coal and petroleum coke with an average sulfur content of 1.2 percent and a moisture content of 22 percent. Figure 3-11 shows the results of the parametric testing. These tests were conducted at a 35°F approach to saturation at the dryer outlet. Figure 3-12 shows the results of a seven-day demonstration test, plotted as daily average SO_2 removal, with the same low sulfur fuel. At a 35°F approach, SO_2 removal ranged from about 70 percent at about a 0.75 reagent ratio to about 80 percent at a 1.2 reagent ratio. The results of a second demonstration run designed to demonstrate 90 percent SO_2 removal at an 18°F approach showed an average 93 percent SO_2 removal.

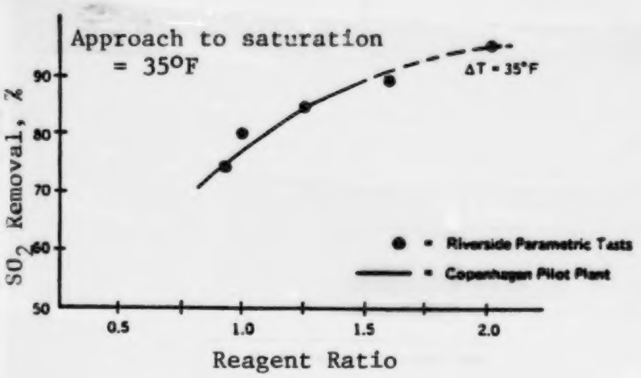


Figure 3-11. Low sulfur coal parametric tests - Riverside.

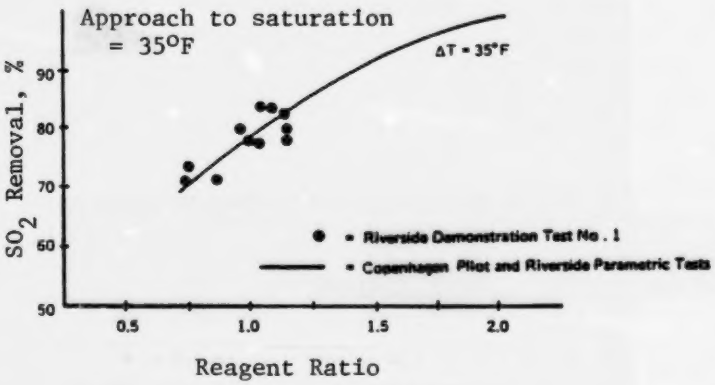


Figure 3-12. Low sulfur coal demonstration test results - Riverside.

Source for Figures 3-11 and 3-12: Meyler and Felsvang. (See Information Sources at the end of this section.)

However, no reagent ratio data were provided for this second low sulfur fuel demonstration test.

Joy/Niro reported that operation of the spray dryer was trouble-free and that both spray dryer and fabric filter solids were dry and easy to handle. Figure 3-13 shows the measured residual moisture in the spray dryer as a function of approach to saturation for two different atomizer speeds. These data show that the residual moisture content of the product increases as the approach to saturation at the dryer outlet is decreased. Thus, although SO_2 removal is increased at a closer approach, the dryer design and operation is constrained by the need to maintain a dry, free-flowing product.

The stated objective of the high sulfur coal test series was to define the conditions required for 90 percent or greater SO_2 removal. During this test series, the Riverside boilers fired an Illinois bituminous coal. The coal and fly ash analyses are shown in Table 3-6. The average sulfur content of the coal was 3.2 percent, resulting in about 2000 ppm SO_2 at the inlet to the spray dryer. An analysis of the slaking water used is shown in Table 3-7.

Results of the parametric testing with high sulfur coal are shown in Table 3-8. The results showed that 93 percent SO_2 removal was achievable at both an 18 and a 35°F approach to saturation. A 1.34 reagent ratio was required to achieve this removal at an 18°F approach, while a 1.6 reagent ratio was required at a 35°F approach. For a 7-day (168-hr) demonstration run, the following results were reported:

- 93.6% SO_2 removal (7-day rolling average),
- reagent ratio of 1.37,
- 35% solids slurry (with recycle), and
- "fine" atomization.

In reporting the results, Joy/Niro noted that for higher sulfur coal operation, the increasing percentage of lime (increasing reagent ratio) results in a more viscous slurry. Thus, to operate at a constant viscosity for pumping, the slurry was maintained at 35 percent solids (with recycle) rather than the "normal" operating condition of 40 percent for lower sulfur coal tests. Joy/Niro also stated, however, that site-specific economic factors could result in the optimal solids content of greater than 35 percent for some high sulfur applications.

The team also conducted extensive fabric filter testing at Riverside. The test program for the fabric filter was designed to evaluate fabric strength and fabric life of various bag materials, characterize fabric filter collection efficiency and pressure drop both with and without the spray dryer in service, and determine the effects of "long-term" operation at a close approach to saturation at the dryer outlet. The reported results indicated the following:

- Teflon-coated fiberglass bags had low failure rates with failures apparently limited to those bags damaged during installation. Two fiberglass bag materials with a silicon, graphite, and teflon

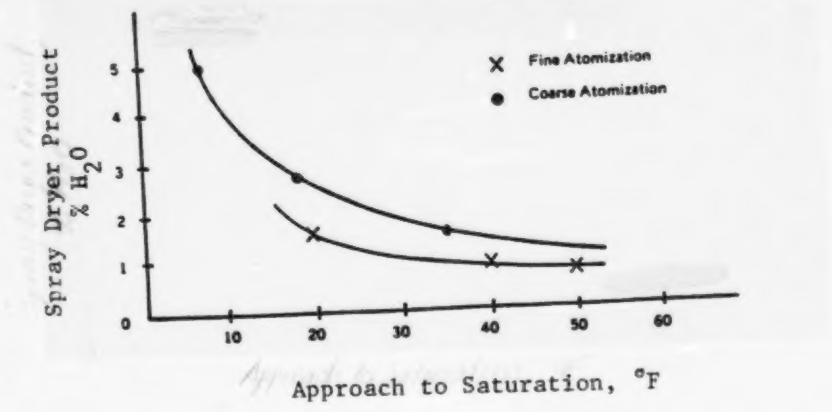


Figure 3-13. Spray dryer product moisture as a function of approach temperature - Riverside.

Source: Meyler and Felsvang. (See Information Sources at the end of this section.)

TABLE 3-6. RIVERSIDE HIGH SULFUR COAL ASH ANALYSES

Coal - Ultimate Analysis (weight %)

Component	Average	Range
Carbon	60.5	59.2 - 63.8
Hydrogen	4.33	4.13 - 4.62
Nitrogen	1.17	1.10 - 1.28
Oxygen	7.74	7.45 - 8.07
Sulfur	3.19	2.91 - 3.44
Moisture	13.0	10.3 - 15.8
Ash	10.4	8.54 - 12.1
Btu/lb	10915	10724 - 11449

Fly Ash - (weight %)

Component	Average
SiO_2	45
Al_2O_3	19
Fe_2O_3	15
TiO_2	1.0
CaO	5.6
MgO	1.5
Na_2O	1.0
K_2O	2.1
P_2O_5	0.25
SO_3	1.5

Source: Kaplan, et al. (See Information Sources at the end of this section.)

TABLE 3-7. RIVERSIDE SLAKING WATER ANALYSIS

Component	mg/ℓ
Ca(as $CaCO_3$)	314
Mg(as $CaCO_3$)	111
SO_4	672
Cl	14
Fe	0.8
CO_3	0
HCO_3	133
Total Dissolved Solids	1142
Total Suspended Solids	78
pH	7.7
Total Alkalinity (as $CaCO_3$)	109

Source: Meyler and Felsvang. (See Information Sources at the end of this section.)

TABLE 3-8. RESULTS FROM HIGH SULFUR COAL PARAMETRIC TESTS

Test No.	(Units)	1	2	3
Gas Flow	acfm	531,000	510,000	470,000
Temperatures:				
Inlet to dryer	°F	331	316	315
Outlet of dryer	°F	164	156	145
ΔT_{as}^{a}	°F	32	35	18
SO_2 Concentrations:				
Inlet to dryer	ppmv	2,089	2,054	1,946
Outlet of fabric filter	ppmv	128	192	124
SO_2 Removal	%	93.8	90.6	93.5
Feed Slurry	% solids	33.7	34.4	32.5
Atomization		FINE	FINE	VERY FINE
Average Fabric filter ΔP	in. w. g.	5.1	4.3	3.5
Reagent Ratio		1.60	1.46	1.34
Product Moistures:				
Spray dryer product	%	1.28	1.32	0.95
Fabric filter product	%	0.82	1.06	0.90

[a] Approach to saturation

Source: Kaplan, et al. (See Information Sources at the end of this section.)

tri-coated finish exhibited unacceptably high failure rates. The polyester bags tested were subject to "temperature limitations," presumably during periods when the spray dryer was not operated, and were not in service long enough for full evaluation. (No results were reported for acrylic bags, a fabric which has been specified for some commercial spray drying systems.)

- In testing without the spray dryer in operation, outlet particulate matter emissions were in the range of 0.003 to 0.006 gr/acf, with opacities of less than 5 percent. (The inlet grain loading without the spray dryer in operation averaged between 1.2 and 2.9 gr/acf.) Pressure drop across the fabric filter was reported to be between 4.5 and 5.0 in.w.g., and flange-to-flange temperature drop averaged less than 5°F.

- With the spray dryer in operation, inlet dust loadings increased to between 4.3 and 12.1 gr/acf. Outlet loadings, however, were between 0.001 and 0.02 gr/acf. The higher loading was attributed to broken bags. Joy/Niro reports that the fabric filter collection efficiency was higher when the spray dryer was in service. Baghouse pressure drop was 5 in. w.g. or less when the spray dryer was in operation.

- During the first 6 months of Riverside operation (system check-out and low sulfur fuel testing), corrosion rates measured with sample coupons were less than one mil per year, a rate within the design allowance. No fabric filter corrosion rates were given for the fabric filter during high sulfur coal testing. Spray dryer corrosion rates for both low sulfur and high sulfur coal testing are shown in Table 3-9. These data show higher corrosion rates for the higher sulfur coal tests, but only 6 weeks of data were available for high sulfur coal testing versus 9 months of data for the low sulfur tests. Emissions measurements showed that the spray dryer reduced flue gas SO_3 levels to the lower end of the test method's detection limit (about 0.3 ppm) even when higher sulfur coal was fired.

- Joy/Niro has concluded that no significant corrosion will occur during extended operation at a close approach (18°F), provided that internal components are maintained at least 10°F above the adiabatic saturation temperature of the gas and that localized condensation is prevented by adequate insulation. Special attention is recommended for access doors and minimizing operating time with intercompartment walls at temperatures below adiabatic saturation.

Joy/Niro also collected data on the system as operated with one of the existing ESP's instead of the fabric filter used for particulate collection. During the low sulfur fuel tests, the ESP's achieved 95.91 to 99.75 percent efficiency with the spray dryer in service. The inlet grain loading ranged from 3.26 to 9.26 gr/acf, while the operating specific collection area (SCA) ranged from 158 to 208 ft^2/1000 acfm. Based on the results of Riverside and previous testing, Joy/Niro has identified factors that should be considered in selecting an ESP over a fabric filter, including:

TABLE 3-9. AVERAGE CORROSION RATES IN THE SPRAY DRYER

Time Period	Coal Type	Central Gas Disperser	Spray Dryer	Spray Dryer Outlet
November 18, 1980 to September 1, 1981 (9 months)	Montana Low Sulfur	0.75[a] (0.44-0.96)[b]	1.46 (1.17-2.28)	2.01 (1.23-3.7)
September 1, 1981 to October 9, 1981 (6 weeks)	Illinois High Sulfur	0.61	5.3	0

[a] All values mils/year.

[b] Numbers in parentheses are the range of measured values.

Source: Kaplan, et al. (See Information Sources at the end of this section.)

- SO_2 removal requirements,
- fly ash resistivity (ESP may have to be sized to handle full flow of gas when the spray dryer is not in operation),
- economics of pressure drop-related costs (an ESP will typically have lower pressure drop than a fabric filter), and
- the amount of recycle to be used (higher dust loadings associated with recycle require a larger, more expensive ESP).

In addition to evaluating spray dryer system performance at Riverside, Joy/Niro has been evaluating the characteristics of the wastes produced as well as potential disposal or utilization methods. Their work in this area is discussed in Section 5, Waste Disposal.

Commercial Activities

Joy/Niro was awarded two new utility spray drying systems in October 1982, and they have sold two new industrial systems. The status of Joy/Niro's commercial systems is shown in Table 3-10. Joy/Niro was awarded the Cajun Electric and Northern States Power systems this fall. No details on these systems are available yet. The 860 MWe Sherburne County system is the largest spray drying system sold to date.

The system sold to General Motors' will treat flue gas from a boiler firing 1 to 3 percent sulfur Indiana bituminous coal. The lime-based system will have a single spray dryer, equipped with a rotary atomizer, followed by a pulse-jet fabric filter. Solids recycle will be used. For the Fairchild Air Force Base sale, Joy/Niro will supply spray dryer/fabric filter systems to treat flue gas from boilers fired with a 1 percent sulfur western subbituminous coal.

The Argonne system has been operating since December 1, 1981. Results from operation of this system are discussed in more detail in Section 4, but the system has passed initial compliance tests, demonstrating 79.7 percent to 95.6 percent SO_2 removal at boiler loads ranging from 35 to 82 percent. The boiler fired a 3 percent average sulfur coal during the performance tests. Sixty-day reliability tests and final performance tests were scheduled for the summer and fall of 1982.

Future Activities

Joy/Niro currently has a few utility system and several industrial bids outstanding. Regarding the industrial market, however, a Joy/Niro spokesman indicated that delays in proposal of industrial boiler new source performance standards (NSPS) and the perception of changing environmental priorities may have stalled industrial FGD system sales. Exceptions might come in cases where FGD is required to meet local or state SO_2 regulations.

Testing at Riverside is to be conducted through the end of 1982. Joy/Niro is currently testing with a Sarpy Creek low sulfur coal at the request of Northern States Power.

TABLE 3-10. STATUS OF JOY/NIRO COMMERCIAL SPRAY DRYING SYSTEMS

System Purchaser	Location	Size	Status/Startup Date
Basin Electric	Antelope Valley, Unit 1 (Beulah, ND)	440 MWe	May 1983 (Under construction)
Basin Electric	Antelope Valley, Unit 2 (Beulah, ND)	440 MWe	April 1985
Tucson Electric	Springerville, Unit 1 (Springerville, AZ)	370 MWe	June 1985
Tucson Electric	Springerville, Unit 2 (Springerville, AZ)	370 MWe	June 1987
Platte River Power Authority	Rawhide, Unit 1 (Fort Collins, CO)	280 MWe	December 1983 (Under construction)
Sunflower	Holcombe, Unit (Hav, KS)	319 MWe	June 1983 (Under construction)
Northern States Power Company	Sherburne County, Unit 3 (Becker, MN)	860	Awarded in Fall, 1982
Cajun Electric	Oxbow, Unit 1 (Coushoutta, LA)	565	Awarded in Fall, 1982
Argonne National Labs	Argonne, IL	170,000 lb steam/hr	Operating; has not yet been turned over to Argonne
GM-Buick Motors Division	Flint, MI	450,000 lb steam/hr	Under construction; startup date not set
Fairchild Air Force Base	Units 1, 2, 3 Spokane, WA	110,000 lb steam/hr each	Under fabrication; late 1983 startup
Calgon (incinerator application)	Catlettsburg, KY	--	July 1982

Joy/Niro also recently announced that they are developing a process aimed at combined SO_2/NO_x removal in the spray dryer. No details were provided on the new process, but Joy/Niro may conduct some testing of the concept at Riverside.

Information Sources

Meyler, J. A. and Karsten Felsvang. "One Year of Operation of the Riverside Dry Scrubber." (Presented at the 44th American Power Conference, Chicago, Illinois, April 26-28, 1982.)

Kaplan, Steven, M., et al. "Dry Scrubbing at Northern States Power Company's Riverside Generating Plant." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20, 1982.)

Meyler, J. A., Joy Equipment Company - Western Precipitation Division. Telephone conversations with M. E. Kelly, Radian Corporation, March 26 and August 17, 1982.

Kaplan, Steven, Niro Atomizer, Inc. Telephone conversation with M. E. Kelly, Radian Corporation, March 26, 1982.

3.14 MIKROPUL CORPORATION/KOCH ENGINEERING COMPANY, INC.

Address:
Mikropul Corporation
10 Chatham Road
Summit, New Jersey 07901

Koch Engineering Co., Inc.
161 East 42nd Street
New York, New York 10017

Contact for More Information:
Tom Reinauer
Mikropul Corporation
(201) 273-6360

Mike Mutsakis
Koch Engineering Co., Inc.
(212) 682-5755

Background

Mikropul is a division of U. S. Filter, which includes Ducon, a wet scrubber manufacturer. Mikropul began work on a spray dryer-based FGD system in January 1978. As the result of their work, Mikropul was awarded a contract in late 1978 to provide a spray dryer/fabric filter system for a coal-fired industrial boiler at Strathmore Paper Company at Woronco, Massachusetts. Mikropul established a working relationship with Koch Engineering in 1979. Koch successfully implemented a redesign of the spray dryer internals at Strathmore to improve SO_2 removal efficiency and solve problems with frequent wetting of the spray dryer walls. As a result of the working relationship developed between Mikropul and Koch during the Strathmore modifications, the two companies have agreed to market dry FGD systems jointly. Koch has been developing spray dryer FGD technology since early 1979.

Research Activities

Koch Engineering's R&D work is currently being conducted at Abcor, Inc. in Wilmington, Massachusetts. Abcor is a wholly owned subsidiary of Koch Engineering. The Abcor facility has a new 5 million Btu/hr pulverized coal-fired boiler. Gas flow from the boiler is approximately 2000 acfm at 350°F (with 40 percent excess air). The facility has two pilot-scale spray dryers, a 40-in. diameter dryer equipped with a two-fluid nozzle atomizer and a 60-in. diameter dryer equipped with a rotary disc atomizer. In addition, the facility is equipped with a reverse-air fabric filter and has the capability to test different coal types, solids recycle, and flue gas bypass.

The FGD pilot plant at Abcor has been in operation since November 1981. In the first phase of testing, Koch conducted parametric testing using the same type of coal and lime being used at Strathmore Paper Company. Variables studied during the testing included reagent ratio, approach to saturation, atomized droplet size, reagent type (calcium- or sodium-based), inlet SO_2 concentration, inlet gas temperature, and lime slaking parameters. The goal of this testing was to determine if results from future pilot studies on other types of coal and lime could be used accurately to predict full-scale system performance. As shown in Figure 3-14 for an approach to saturation of 30°F, the Strathmore data and the Abcor plant data are in good agreement.

The second phase of testing at Abcor will involve a comparison of rotary and nozzle atomizers. The pilot spray dryer system is equipped with a laser set-up capable of measuring droplet or particle size, size distribution, and particle speed at various locations in the spray dryer chamber. Little data comparing droplet size from rotary and nozzle atomizers have been published previously. Koch feels that particles from nozzle atomizers are as small as, if not smaller than, particles from rotary atomizers. The results of these studies will be published upon completion.

After extensive testing on a number of different nozzle designs, Koch has developed a new internal mix nozzle that shows low abrasion, low energy usage, and produces small droplets. The new nozzle design has an energy usage of between 0.8 and 1.0 hp/1000 cfm vs. 3 hp/1000 cfm for the external mix Koch-Lurgi nozzle currently used at the Strathmore installation. In addition, the new nozzle has larger openings to help reduce lime plugging problems. In recent laboratory tests, the new nozzle design showed zero abrasion after 3 months of continuous operation. This new nozzle will be used in the particle and droplet size tests to be conducted at the Abcor facility.

In studies at Strathmore, Koch tested various types of limes, including high calcium pebble lime, granulated lime, pulverized lime, and dolomitic lime. The application of high alkalinity waste lime products was also investigated. Koch found that for the Strathmore system, the high calcium pebble lime produced the best slurry. The primary problem with the other lime

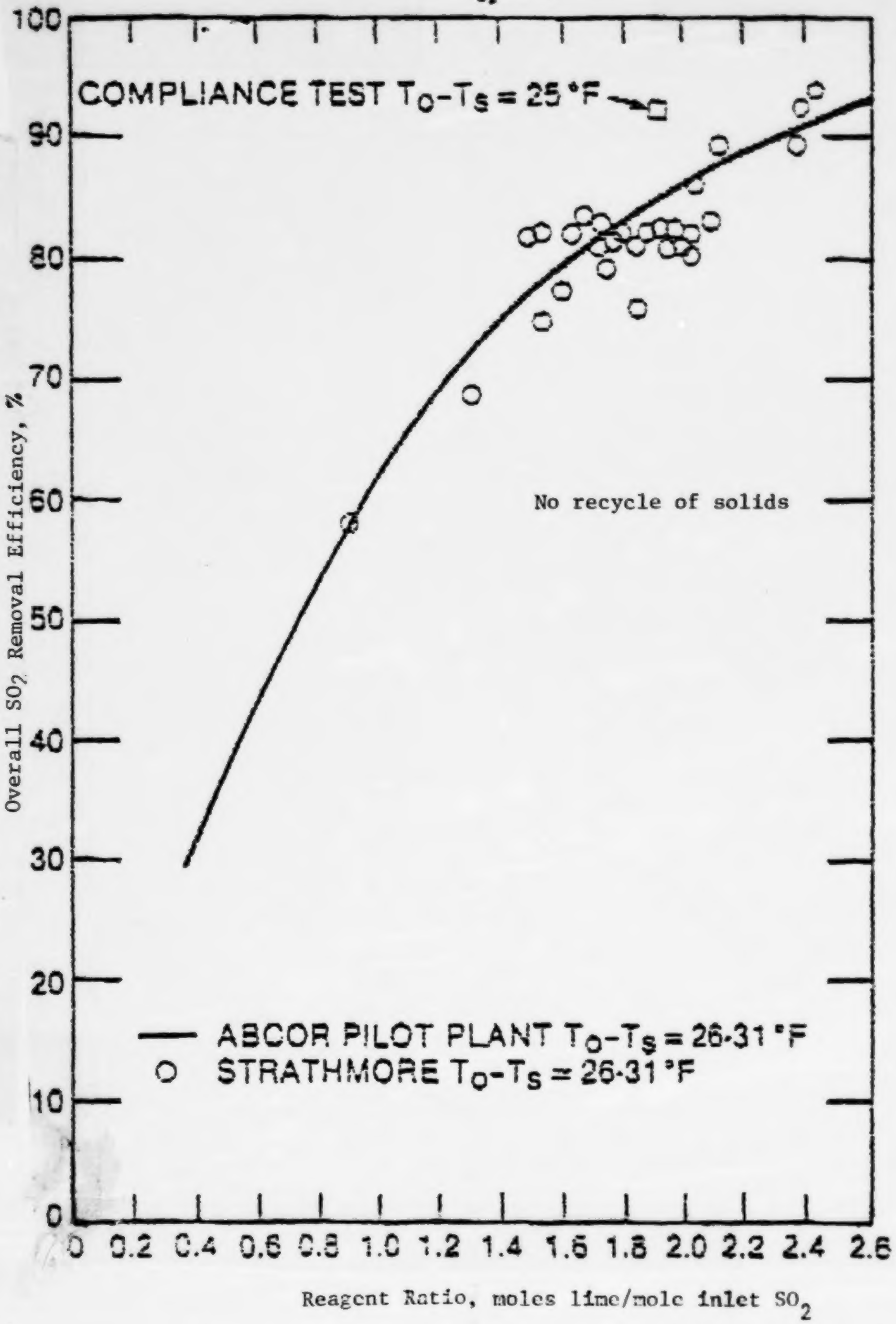


Figure 3-14. Comparison of ABCOR pilot plant and Strathmore results.

Source: Reinauer T. V. and M. Mutsakis (See Information Sources at the end of this section.)

types, in particular the dolomitic lime, was that high solids contents were required for maximum sulfur removal when burning higher sulfur coals (greater than 1 to 2 percent). The SO_2 removal was limited by the ability or inability to produce a low viscosity slurry with a solids content greater than 20 percent (See Section 4.1).

Commercial Activities

Mikropul's lime-based spray dryer/fabric filter system at Strathmore has now been in operation for more than two years. FGD system availability during this period has been more than 97 percent. Strathmore's 65,000 lb steam/hr pulverized coal boiler burns about 75 tons of coal/day. The sulfur content of the coal ranges from 1 to 5 percent sulfur by weight, with present coal specifications calling for 3 percent sulfur. In March 1981, the Strathmore system achieved compliance performance (emission limit 1.2 lb $SO_2/10^6$ Btu) on an average 3.8 percent sulfur coal. The results of EPA Method 6 emission tests conducted by a third party (Mostardi-Platt Co.) showed overall FGD system efficiency ranging from 90.1 percent to 96.6 percent with an average outlet emission rate of 0.410 lb $SO_2/10^6$ Btu. The tests were conducted at an average reagent ratio of 1.9.

The spray dryer at Strathmore was modified by Koch Engineering in March 1980 to improve flue gas and slurry mixing. The 14.5-ft diameter by 28-ft high spray dryer has four two-fluid nozzle atomizers. Replacement of the nozzle lance assembly can generally be accomplished in only a few minutes by a trained operator.

During initial start-up of the Strathmore system, Mikropul found that the initial set of filter bags in the baghouse shrank over the retainer and did not respond properly to the cleaning process. Mikropul determined that the cause of the problem was the heat setting procedure used during the manufacture of the felt. At their laboratory in Summit, New Jersey, Mikropul developed an improved heat setting procedure and a second set of bags was manufactured and installed. This second set of filter bags was only recently replaced and remained in service for more than 30 months with only 5 percent bag replacement during the period. Mikropul feels that acrylic is the best material for fabric filters on dry FGD systems where temperature does not exceed 300°F.

Waste products from the Strathmore system are discharged from the baghouse hoppers into portable containers that are carried to an off-site disposal area. During 1981, solid waste from the site included 4200 tons of dry FGD waste products plus approximately 2600 tons of fly ash. At the same time, the FGD system reduced SO_2 emissions from the site by nearly 1000 tons.

Information Sources

West, Woody, Mikropul Corporation. Telephone conversation with M. A. Palazzolo, Radian Corporation, April 5, 1982.

Mutsakis, Mike, Koch Engineering. Telephone conversation with M. A. Palazzolo, Radian Corporation, April 8, 1982.

Reinauer, T. V. and M. Mutsakis. "Dry Flue Gas Desulfurization." (Presented at the 1981 Engineering Conference of the Technical Association of the Pulp and Paper Industry, September 28-October 1, 1981.)

Reinauer, T. V., et al. "Dry FGD on an Industrial Boiler: 20,000 hours of Operating Experience. (Presented at the AICHE Summer National Meeting, Cleveland, Ohio, August 29 - September 1, 1982.)

3.15 ROCKWELL INTERNATIONAL

Address: Environmental & Energy Systems Division
Rockwell International
Energy Systems Group
8000 DeSoto Avenue
Canoga Park, California 91304

Contact for More Information: Dr. Dennis G. Gehri, Project Manager
ACP Research, Development and Applications
Rockwell International
(213) 341-1000, ext. 2513

Background

The former Rockwell International/Wheelabrator-Frye joint venture sold two commercial systems: a utility system to Otter Tail Power Company (Coyote Station) for a 410 MWe utility boiler and an industrial system (65,000 acfm) to Celanese Fibers Company. Both are spray dryer/fabric filter systems.

Since the dissolution of the joint venture in early 1981, both Rockwell and Wheelabrator-Frye have continued to be involved in dry FGD projects. For future commercial sales, Rockwell will bid the entire system and subcontract the particulate collection portion of the process.

Research and Development

Rockwell is continuing to conduct R&D studies with the 5000-acfm pilot spray dryer installed at Commonwealth Edison's Joliet Station. Studies conducted have been directed toward the optimization of spray dryer and fabric filter performance. Rockwell has also been conducting some research in the area of waste disposal. However, the results of these studies are considered proprietary.

Rockwell's mobile unit is still located near their Canoga Park facility. The unit may be moved to an eastern utility site in the near future.

In general, Rockwell's future R&D efforts will focus on (1) improving the design of spray dryers and (2) improving the regeneration cycle of their regenerable aqueous carbonate spray drying process.

Commercial Activities

Rockwell has sold one dry FGD system since the end of 1980. Sierra Pacific Power and Light has purchased the system for its North Valmy Station in Valmy, Nevada. The FGD system, which will treat 1,200,000 acfm of flue gas from a 270 MWe subituminous coal-fired boiler, consists of three spray dryers, each with three rotary atomizers, and has a 76 percent SO_2 removal guarantee for 0.4 to 1.0 percent sulfur coal. Lime will be used as the reagent and a fabric filter will be used for solids collection. The system will use both warm gas bypass and solids recycle. Startup is planned for 1985.

The Coyote FGD system, which uses commercial soda ash as a reagent, is currently operational, and many modifications have been made to improve performance. Modifications have primarily centered on the atomizers. The major problem during initial startup of the Coyote system was wet droplets hitting the spray dryer chamber walls, resulting in a build-up of solids. The build-up was attributed primarily to poor atomization resulting from inadequate atomizer design. Other factors, including incorrect vertical positioning of the atomizers, faulty vane ring design, and spray machine failures were said to have "aggravated" the build-up problem, but the build-up was said not to be a result of inadequate dryer residence time.

Rockwell successfully redesigned the atomizer and the atomizer shaft and modified the gear box to reduce mechanical failures of the atomizer. Rockwell's spray machine and atomizer design modifications have reportedly significantly improved performance, allowing operation at about a 50°F approach to saturation with "negligible" solids build-up. Build-up free operation with the original atomizer was limited to an 80°F approach, which limited SO_2 removal to 60 percent.

Performance tests on the Coyote system have been reported for two sets of operating conditions. The results are shown in the table below.

TABLE 3-11. PERFORMANCE DATA FOR COYOTE SYSTEM

ΔT_{AS}(°F)[a]	ΔT_{SD}*(°F)[b]	SO_2 Removal (%)	Reagent Ratio[c]	Build-up
65	105	70	0.93 (75% reagent utilization)	"none"
50	120	70	0.74 (>95% reagent utilization)	"relatively minor" build-up

Note: Coyote performance guarantees are a minimum 70% SO_2 removal for all fuels with a sulfur content between 0.6 and 1.42%, and 75 percent reagent utilization.

[a] ΔT_{AS} = approach to adiabatic saturation temperature.

[b] ΔT_{SD} = gas-side temperature drop over the spray dryer.

[c] Reagent ratio is moles Na_2O/mole inlet SO_2.

The high reagent utilizations for the Coyote system may be due in part to the contribution of lignite fly ash alkalinity to SO_2 removal, even though the system does not employ solids recycle.

Although relatively minor wall build-up may be experienced at the 50°F approach to saturation, the cost savings in soda ash usage should more than offset any clean out costs, according to Montana-Dakota Utilities, the station operator. Figures 3-15 and 3-16 show performance data for the Coyote system as reported at the 1982 EPA/EPRI FGD Symposium.

The fabric filter at Coyote has been operating satisfactorily since system startup in mid-1981. Compliance testing and utility acceptance of the spray dryer/fabric filter system are expected for the Fall of 1982.

The Celanese industrial boiler system has been operating since early 1980 without any major problems. The system passed compliance tests in February 1980. In tests conducted by Rockwell with a 1.5 to 3 percent sulfur coal, the Celanese system achieved SO_2 removal efficiencies in excess of 90 percent during once-through operation. No reagent ratio was reported for these tests.

Rockwell currently has several outstanding bids for utility FGD systems.

Information Sources

Gehri, Dennis, Rockwell International. Telephone conversation with M. A. Palazzolo, Radian Corporation, March 30, 1982 and August 20, 1982.

Lewis, Merrill, Montana-Dakota Utilities Co. Telephone conversation with M. E. Kelly, Radian Corporation, March 26, 1982.

Lewis, M. F. and D. C. Gehri. "Atomization - The Key to Dry Scrubbing at the Coyote Station." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida. May 17-20, 1982).

3.16 WHEELABRATOR-FRYE, INC

Address: Wheelabrator-Frye, Inc.
Air Pollution Control Division
600 Grant Street
Pittsburgh, Pennsylvania 15219

Contact for More Information: Peter Maurin
Director, FGD Systems
(412) 288-7300

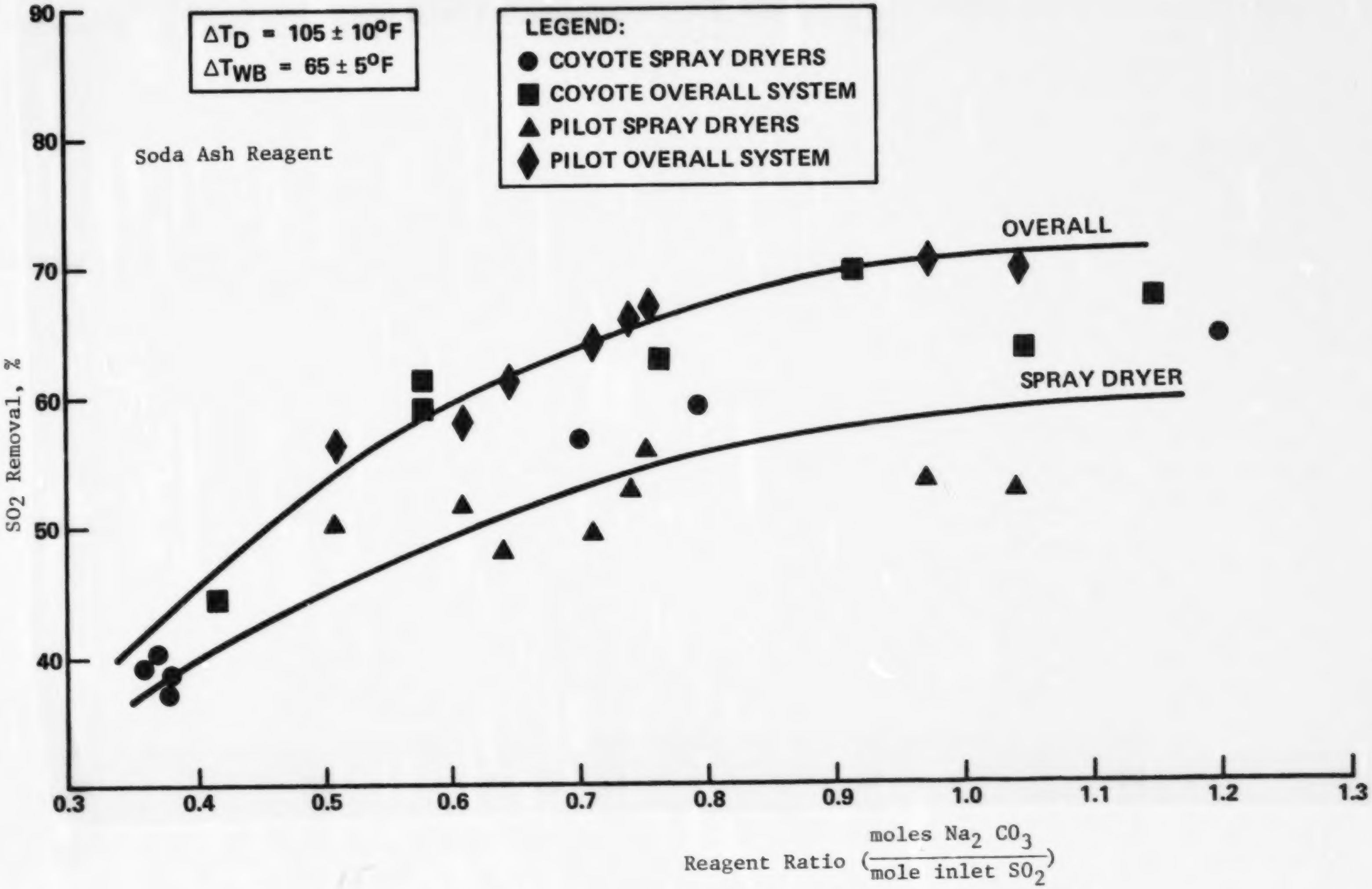


Figure 3-15. Coyote performance data at 65°F wet-bulb temperature (ΔT_{WB})
Source: Lewis, M. F. (See Information Sources at the end of this section.)

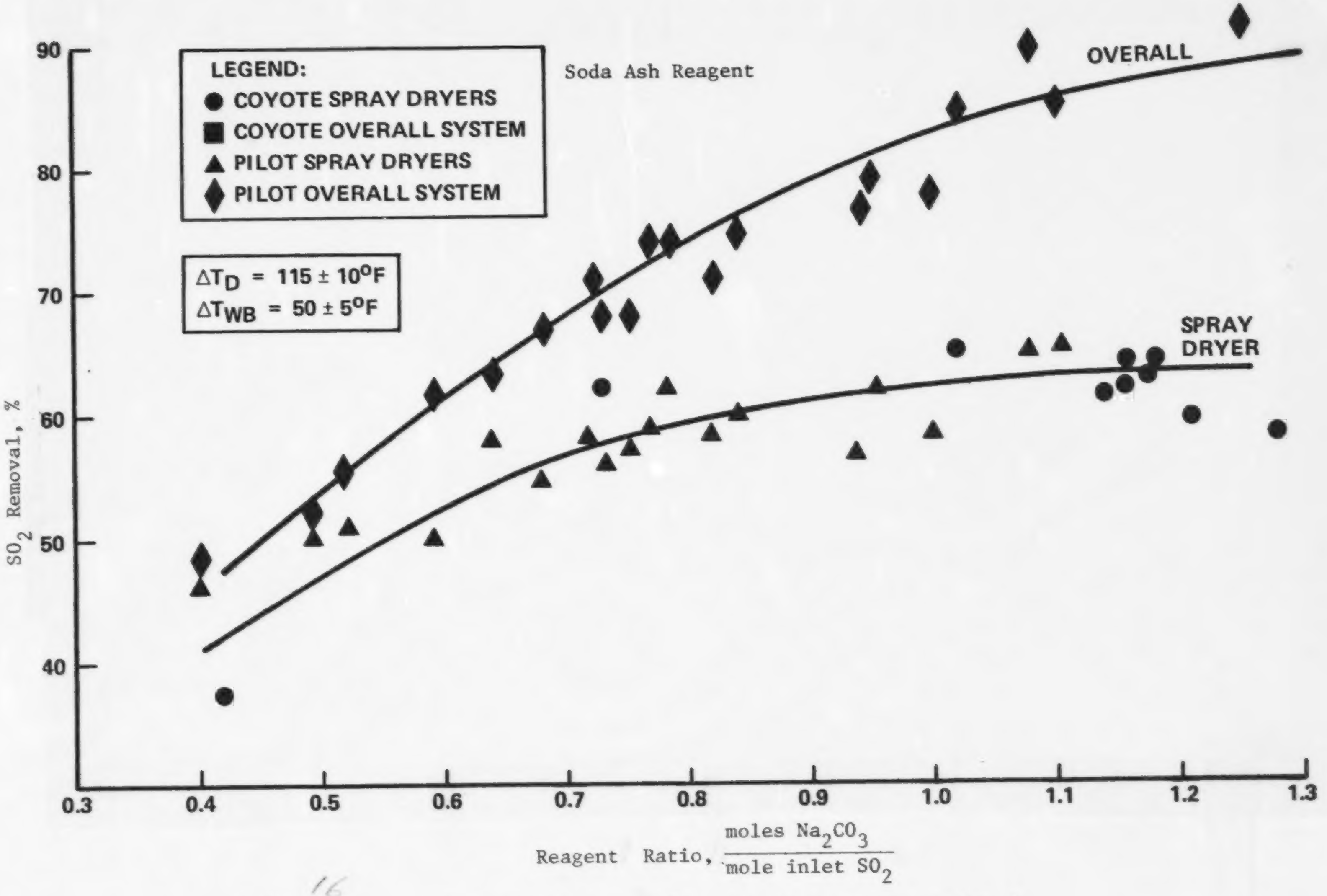


Figure 3-16. Coyote performance data at 50°F wet-bulb temperature (ΔT_{WB}).
Source: Lewis, M. F. (See Information Sources at the end of this section).

Background

The Wheelabrator-Frye/Rockwell International venture has sold two commercial systems: to Otter Tail Power Company (Coyote Station) for a 410 MWe utility boiler and an industrial system (65,000 acfm) to Celanese Fibers Company. Both are spray dryer/baghouse systems.

Wheelabrator-Frye and Rockwell dissolved their joint venture in January 1980. Both companies are continuing to be involved in systems sold by their joint venture. In addition, Wheelabrator-Frye is continuing active involvement with dry FGD work, drawing on experience of their divisions and subsidiaries in design, fabrication, and installation of spray dryer/baghouse systems.

Research and Development

Wheelabrator-Frye is currently doing a considerable amount of development work in the area of atomization. Studies are being conducted at three locations, including Commonwealth Edison's Joliet Station, Whiting Corporation's Swenson Division (a Wheelabrator-Frye company) in Harvey, Illinois and Wheelabrator-Frye's Technical Center in Pittsburgh, Pennsylvania. Work is continuing at the Joliet Station on process performance using rotary atomizers, while studies at each of the other locations involve both two-fluid nozzles and rotary atomizers. Studies being conducted on two-fluid nozzles include flow models of various chamber design concepts and the effects of nozzle service life on droplet size. Studies on rotary atomizers relate to the optimization of spray patterns through the improvement of atomizer design and scale model studies of gas patterns in rotary atomizer spray chambers.

Wheelabrator-Frye is continuing to study both atomizer types because they feel that while rotary atomizers are more applicable to large utility systems, the simplicity of nozzles is more attractive for industrial applications. The company also feels that the relative advantages and disadvantages of each atomizer type are less important for systems in the size range of 50,000 to approximately 250,000 acfm.

Commercial Activities

Wheelabrator-Frye has sold a dry FGD system to Austell Box Board Company in Austell, Georgia to treat flue gas from a pulverized coal-fired boiler (250,000 lb/hr of steam). The FGD system will handle 171,000 acfm of flue gas at 350°F. The fuel is a bituminous coal with a sulfur content of between 1.0 and 2.5 percent.

The FGD system, which consists of a single spray dryer with 12 two-fluid nozzles and a pulse-jet fabric filter, will use lime as the sorbent. Lime will be slaked in a detention slaker. Provisions have been made for solids recycle if desirable under higher sulfur coal conditions.

The joint venture Rockwell/Wheelabrator-Frye dry FGD system at Otter Tail Power Company and Montana/Dakota Utilities' Coyote Station started operation in February 1981. The fabric filter at Coyote Station has had no trouble meeting particulate standards. Less than one-half percent of the 7752, 12-in.x 30 ft long bags had failed after 10 months of operation. Through the use of different fabric types in "test compartments" of the fabric filter, Wheelabrator-Frye has found that acrylic bags have demonstrated good strength retention and operate with higher throughput and lower pressure drop (approximately 1 inch of water less) than other fabrics. Other bag types tested include fiberglass, Nomex,and polyester. The only bag material that has shown poor performance is a certain polyester.

The other joint venture dry FGD system at Celanese Fibers' Amcelle Plant began operation in January 1980. The dry FGD system returned to service in early 1982 after being shut down over the winter due to low product demand. During that time, the boiler operated at very low loads with only the fabric filter in service.

Wheelabrator-Frye's involvement with dry injection work during the early 1970's has indicated that the technology is feasible for most low sulfur applications. However, the company feels that the cost of additives and sorbents makes the technology uneconomical except for special applications.

Wheelabrator-Frye has sold a dry injection system to Kaiser Aluminum that is scheduled for startup in the next few weeks. The system will control SO_3 emissions from a petroleum coke calciner at Kaiser's primary aluminum smelting plant in Chalmette, Louisiana. The dry injection system consists of a pulse-jet fabric filter coated with a waste alkaline material from a local cement plant. The alkaline material is reject kiln dust from a limestone calciner and probably contains both lime and limestone.

The dry injection system is expected to remove greater than 87 percent of the SO_3, (reducing emissions from 40 ppm to less than 5 ppm) in the 110,000 cfm gas stream from the coke calciner. The alkaline material will be injected into the gas stream until a set pressure drop is achieved across the fabric filter. Both the outlet SO_3 concentration and the fabric filter pressure drop will be monitored. The filter bags will be cleaned and recoated when either the outlet SO_3 concentration or the pressure drop increases to a preset level. The calciner offgas does not contain a significant amount of particulate. The primary intent of the dry injection system is to reduce visible emissions that result from condensation of SO_3 at the stack outlet.

Wheelabrator-Frye has been routinely bidding on both utility and industrial systems. Some of these systems may be awarded sometime during the second quarter of 1983.

Information Sources

Maurin, Peter, Wheelabrator-Frye, Inc. Telephone conversations with M. A. Palazzolo, Radian Corporation. March 16, 1982 and April 5, 1982.

Section 4

TECHNICAL RESULTS FROM SPRAY DRYER SYSTEMS

Since the last survey, considerable information has become available from the operation of full-scale spray dryer FGD systems. This information is summarized in this section. The focus is on design and operating problems encountered with the full-scale systems, supplemented with recent pilot-plant data where appropriate. SO_2 and particulate removal performance data are also presented. Most of the information presented is based on recent experience with start-up and operation of the following systems:

- Montana-Dakota Utilities, Coyote Station (Rockwell/Wheelabrator-Frye) - 410 MWe utility system
- Northern States Power Co., Riverside Station (Joy/Niro) - 110 MWe utility demonstration system
- Pacific Power and Light, Jim Bridger Station (Flakt) - 100 MWe utility demonstration system
- Argonne National Laboratory (Joy/Niro) - 170,000 lb steam/hr industrial system
- Strathmore Paper Company (Mikropul/Koch) - 85,000 lb steam/hr industrial system

Selected information from EPA-funded pilot plant studies at Comanche Station (Cottrell Environmental Sciences) and the Martin Drake Station (G.E. Environmental Sciences) and EPRI-funded tests at the Arapahoe Station is also included.

More detail on the full-scale and pilot-scale systems can be found in the appropriate vendor or agency summaries in Section 3.

The information in this section has been organized into five process areas for discussion:

- Section 4.1 Reagent Preparation
- Section 4.2 Atomization
- Section 4.3 Spray Dryer Design and Operation
- Section 4.4 Fabric Filter/ESP Design, Operation, and Performance
- Section 4.5 Solids Recycle

Data on overall system SO_2 removal performance (e.g.,SO_2 removal as a function of reagent ratio for various operating conditions) are presented in Section 4.6.

4.1 REAGENT PREPARATION

In lime-based spray dryer FGD systems the lime is first slaked and then transferred to a slurry hold tank where it is diluted to the desired percent solids before being fed to the atomizer. Slaking can be accomplished in either of three types of slakers: ball-mill, paste or detention. All three types are used in the commercial systems sold to date, although ball mills and paste slakers are more common than dentention slakers. Factors that have been identified as important to reagent preparation are the quality of lime, the quality of the slaking water, and slaking temperature. These factors determine the "reactivity" of the slaked lime slurry.

In some systems, particularly those designed by Joy/Niro, dry recycle solids are added directly to the fresh slurry hold tank. Other options for solids recycle, discussed further in Section 4.5, are (1) combining the fresh feed slurry with a recycle slurry in a separate tank or (2) combining the fresh feed and recycle slurries just upstream of the atomizer.

At the Argonne Laboratory system (which is a Joy/Niro design), the slaked lime slurry is transferred from the paste slaker to the slurry hold tank via rubber-lined centrifugal pumps. Recycle solids are added directly to the feed tank, resulting in about a 40 percent solids slurry that is pumped to the spray dryer. The feed slurry is combined with the bulk of the dilution water just prior to being fed to the atomizer. The dilution water flow is adjusted to provide the desired dryer outlet temperature. Argonne has reported only minor problems with the reagent preparation and feed system (1). Expellers on one pair of centrifugal pumps failed and were replaced with packing and seal water. Also, the slurry mixing tank agitator motor and gear drive were initially undersized for the slurry density at which the system was normally operated.

The reagent preparation and feed system at Northern States Power Co.'s Riverside Station (another Joy/Niro system) is similar to that at Argonne except that both a ball-mill and a paste slaker are available. Joy/Niro has reported only that there are "differences in performance" between the two slaker types, but that these differences are not "significant" in the operation of the spray dryer system (2). They have also reported that only minor mechanical adjustments were required for the reagent preparation and feed slurry equipment and that they have not encountered any major problems with the system. The feed slurry piping design for Joy/Niro systems includes recirculating loops to maintain flow velocities in the 5- to 10-ft/sec range regardless of the flow rate. The carbon steel slurry tanks, which have no special liners, originally had rubber-covered single blade agitators. Due to the inability of this agitator design to provide adequate mixing, they were replaced with stainless steel, dual pitched-blade agitators. The only reported evidence of corrosion in the feed system to date has been in high velocity areas such as control valves (3).

During the high sulfur coal tests at Riverside, Joy/Niro found that the higher percentage of lime in the feed slurry (resulting from the increased reagent ratio requirements) produced a more viscous slurry. Therefore, to operate at a constant viscosity (for pumping purposes), the slurry was maintained at 35 percent solids rather than the "normal" operating level of 40 percent solids used in lower sulfur coal tests. It should be noted that Joy/Niro feels that site-specific considerations might make operation at 40 percent solids desirable for some high sulfur coal applications. A case in point is the Argonne system, a 3 to 3.5 percent sulfur application where the feed slurry is generally about 40 percent solids.

Similar viscosity-related observations were reported by the Mikropul/Koch team based on its experience with the Strathmore system. The team reported that maximum SO_2 removal for this high sulfur coal application was limited by the ability to produce a low viscosity fresh lime slurry beyond a solids content of 20 percent (4). The difference between the 20 percent solids limitation reported by Mikropul/Koch and the 35 to 40 percent solids reported by Joy/Niro may be attributable to the fact that solids recycle is not used in the Strathmore system. A 20 percent solids slurry of fresh lime is more viscous than a 20 percent solids slurry containing lime, calcium sulfite and sulfate product solids, and fly ash.

The Strathmore system uses a detention slaker. Mikropul/Koch has reported that problems with this system were related primarily to development of operator techniques and training and to adjusting the slaker conditions for various types of lime. The team also reported problems with the volumetric lime feeder, and stated that it tends to favor gravimetric feeders for future applications (4).

Cottrell Environmental Sciences conducted a series of spray dryer system runs under various lime slaking conditions as part of the EPA-funded Comanche pilot program (See Section 3.3). The Comanche pilot-scale spray dryer system was equipped with a pugmill paste-type slaker. The tests were designed to investigate the effects of slaking temperature, slaking water quality, and slaker "paddle" speed (5).

The slaking temperature was varied from 160 to 190°F, but there was no discernable effect on SO_2 removal. Normal process water (226 ppm sulfate ion), doped water (1260 ppm sulfate ion), and boiler blowdown water (133 ppm sulfate ion) were each used to slake lime in a second series of tests at 160°F slaking temperature. No difference in system SO_2 removal was reported. However, particle size distributions of lime slaked with the 1260 ppm sulfate ion showed a higher percentage of larger particles (i.e., less reactive surface area) than lime slaked with the lower sulfate waters. Previous test work by others has indicated that about 500 ppm sulfate is about the maximum level desirable for good slaking (7). The fact that no difference in SO_2 removal was observed at Comanche despite the larger slaked lime particles could be attributable to the significantly higher sodium content of the doped tap water (486 ppm vs. less than 10 ppm for the other waters). The sodium could contribute to SO_2 removal in the dryer, compensating for lower lime reactivity.

A lower slaker paddle speed, which results in more complete slaking due to a longer slaker residence time, produced correspondingly slightly higher spray dryer SO_2 removal, according to Cottrell.

4.2 ATOMIZATION

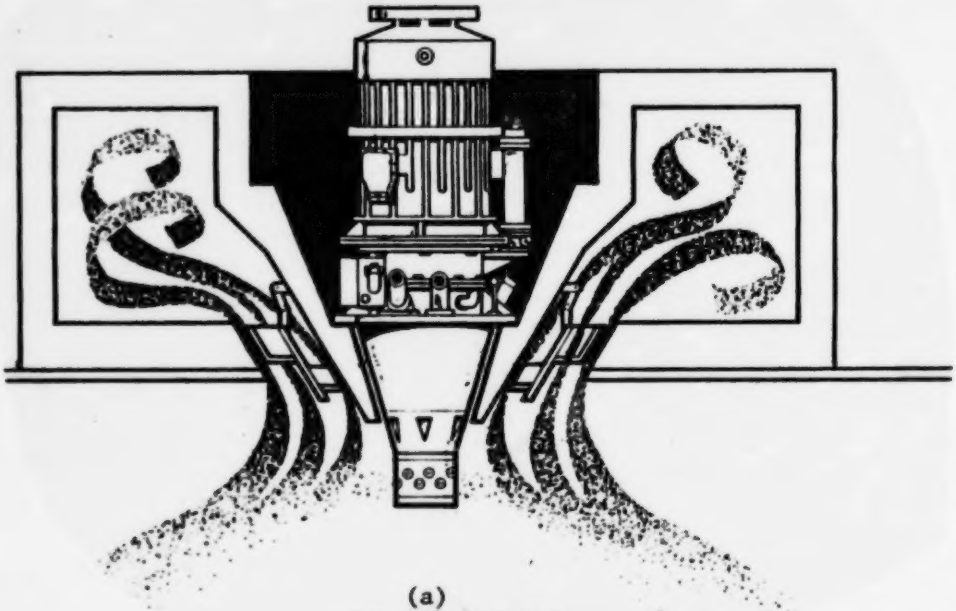
Spray dryers can be equipped with either rotary or nozzle atomizers. Rotary atomizers have been used primarily on a single atomizer per dryer basis, although there are a few systems that have three per dryer. Nozzle atomizers, which use air or steam for atomization, are generally installed in a multiple atomizer per dryer basis. Figure 4-1 shows typical rotary and nozzle atomizer designs. Important considerations in atomizer design include:

- producing small droplets to provide a large surface area for reaction and adequate droplet drying,
- avoiding impingment of atomized spray onto dryer walls, and
- minimizing atomizer pluggage and downtime.

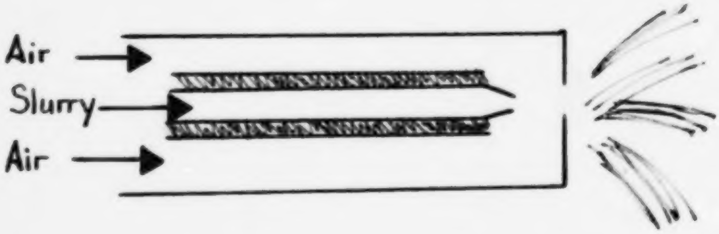
At least three of the operating commercial and pilot-scale systems have reported significant atomization-related problems in their early operation. Some of the problems have been related to poor atomization and the subsequent impingement and build-up of wet solids on the walls of the spray dryer chamber. This problem occurred at the Coyote utility system, which has three rotary atomizers per dryer, and at the Strathmore industrial system, which has four nozzle atomizers. Atomization problems were also encountered at the EPRI Arapahoe pilot plant where a single rotary atomizer is used in the spray dryer.

The full-scale sodium-based system at the Coyote plant operated by Montana-Dakota Utilities has four spray dryers. Each dryer is equipped with three 150-hp rotary atomizers. Each atomizer is designed to handle 25 gal/min. of sodium carbonate solution. The build-up of wet solids on the dryer walls observed in early operation was attributed primarily to poor atomization, but the problem was said to be compounded by improper spray machine vertical position, faulty vane ring design, spray machine failures, and frequent boiler start-up and shut-down (7). The atomization problems required the outlet temperature to be maintained at 70 to 80°F above the adiabatic saturation temperature to prevent solids build-up. At this condition, SO_2 removal was limited to 60 percent versus the system's 70 percent removal guarantee for all coal sulfur contents between 0.6 and 1.42. The initial atomizer wheel supplied by the spray dryer manufacturer proved inadequate for the FGD application. After trying two wheel designs (one with circular openings in the wheel and one with rectangular openings), one of the joint system suppliers (Rockwell International) designed and installed prototype atomizers. The prototype contained a 10-in wheel with over 180 circular openings and a redesigned high speed rotary shaft (See Figure 4-2). The prototypes and subsequent production models installed in the dryers have allowed operation at a 50°F approach with negligible solids build-up.

Reproduced from
best available copy.



(a)
Rotary Atomizer
Courtesy Niro Atomizer, Inc.



(b)
Two-fluid Atomizer
(Externally Mixed)

Figure 4-1. Atomizer types.

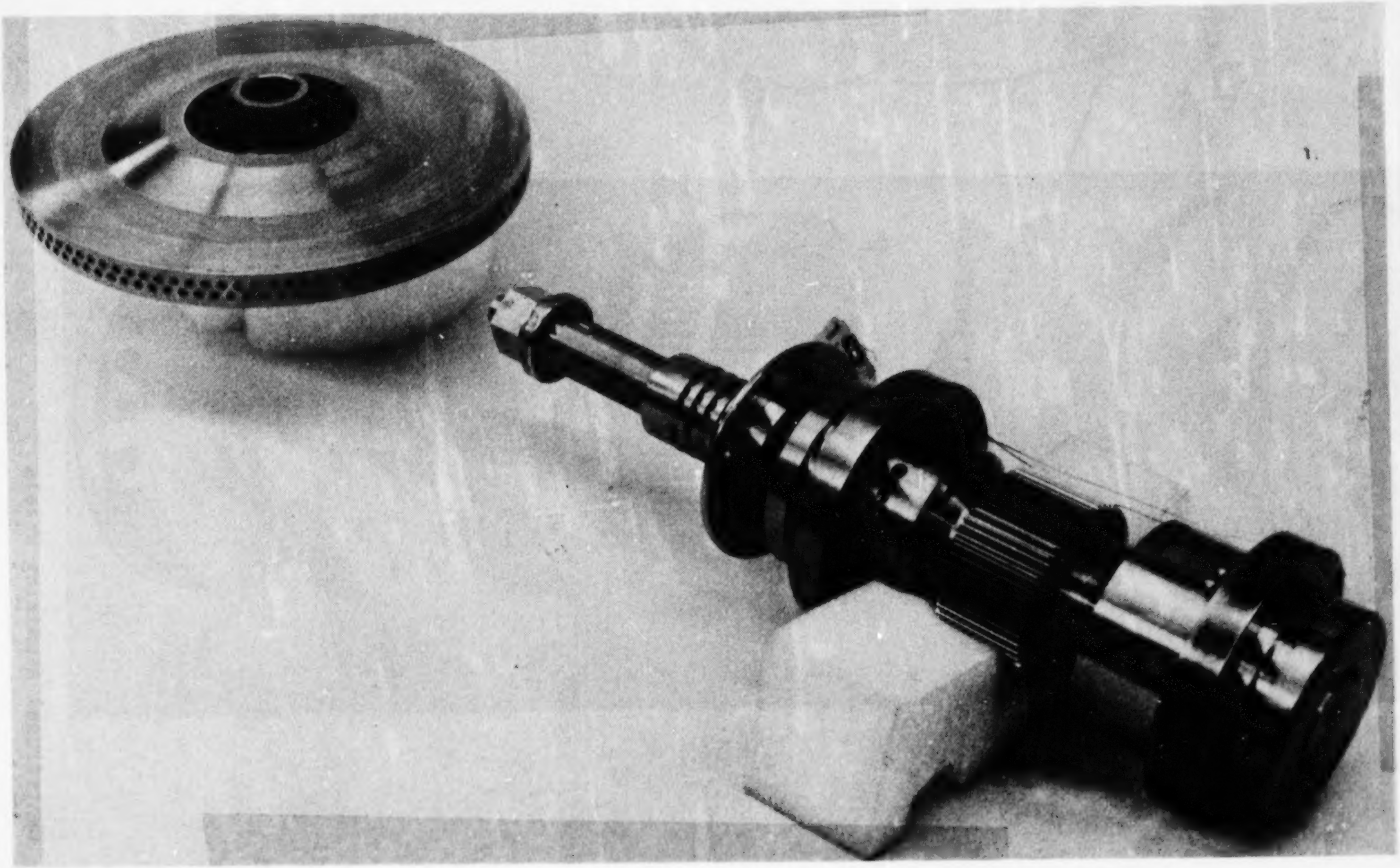


Figure 4-2. Rockwell-designed atomizer for Coyote Station.
Source: Reference 7.

Atomization problems at the Strathmore system were also attributed to atomizer design. Mikropul has reported that the initial two-fluid nozzles provided poor atomization and exhibited high abrasion rates (4). The nozzles were replaced with "improved" two-fluid externally-mixed nozzles. Mikropul is currently working with Koch Engineering to develop further refined nozzles. Koch has developed a new air-atomized internally-mixed nozzle with power requirements of 0.8 to 1.0 hp/10^3 cfm compared to the externally-mixed nozzle power requirement of 3.0 hp/10^3 cfm. The Mikropul/Koch team does not recommend steam-atomized nozzles for lime spray drying systems. It has found that the lime plates out around the nozzle as the slurry is heated during steam atomization, resulting in pluggage of the nozzle.

At EPRI's Arapahoe pilot plant, the atomization problems were related to two factors:

- too many openings (nozzles) in the atomizer wheel, resulting in a low pressure drop through each nozzle and
- operation with a very low percent solids on a once-through (no recycle basis) because of low inlet SO_2 concentration (<400 ppmv).

Both of these problems resulted in plugging of the nozzles in the wheel and poor atomization, forcing shutdown after only a few hours of operation. EPRI switched from the original 12-hole wheel to six-hole and then three-hole wheels. Both have since provided satisfactory operation at a 25 to 30°F approach to saturation. With fewer holes, the pressure drop through each was increased, reducing the settling of lime particles that was thought to contribute to plugging. Operation at higher reagent ratios and with solids recycle has increased the percent solids in the atomizer feed and has also helped reduce plugging problems.

The Riverside and Argonne systems have not reported atomization problems. Both of these Joy/Niro designs are based on the use of a single rotary atomizer in the dryer and a 35 to 40 percent solids feed stream. Thus, it appears that the use of recycle, in addition to providing for potential use of unreacted reagent and fly ash alkalinity, may help improve the operability of a properly designed rotary atomizer.

Flakt has not reported any major atomization problems with their system at Pacific Power and Light Co's Jim Bridger Station. The Jim Bridger unit has 10 two-fluid nozzle atomizers in a vertical spray tower. Flakt suggests that monitoring the atomizing air flow rate to individual nozzles can help indicate when there are problems with a particular atomizer which might warrant by-passing that nozzle (8).

The successful commerical operation of the Strathmore lime spray drying system tends to support claims of vendors that nozzle atomizers can be successfully applied in lime spray drying FGD systems. However, there are no data currently available that allow direct comparison of rotary and nozzle atomizers with respect to SO_2 removal, reagent utilization, reliability, operability, and power consumption under identical process conditions. Some data may be available in the near future, however. EPRI is planning to test nozzle atomizers at their Arapahoe facility, which now uses a rotary atomizer. Also, the Mikropul/Koch team is planning to publish results of detailed studies of both atomizer types on small pilot-scale units. Combustion Engineering and Wheelabrator-Frye are also studying both nozzle and rotary atomizers.

4.3 SPRAY DRYER DESIGN AND OPERATION

The design and operation of the spray dryer is obviously of critical importance in the spray drying FGD process. Most of the commercial systems sold to date have vertical spray dryers, although at least one vendor's design is based on the use of a horizontal reactor. Most of the dryers incorporate a "two-point discharge" design, where some solids fall out of the bottom of the dryer and the flue gas and remaining solids exit the side of the dryer. Good gas distribution is important to assuring intimate contact of the gas with the atomized reagent slurry or solution. At least two system vendors, Joy/Niro and Mikropul/Koch, have devices inside the spray dryer designed to enhance gas/liquid mixing.

The important variables in the trouble-free operation of the spray dryer are inlet gas temperature, approach to saturation at the dryer outlet and gas residence time. These variables, along with atomization quality, determine the degree of dryness of the product solids.

Some of the operating systems have had problems with build-up of wet solids on the dryer walls that were related to spray dryer design and operation. At the Strathmore system, the problems were a result of poor initial dryer design combined with a gas flow 25 to 35 percent higher than the design flow. The higher gas flow, which was attributed to air in-leakage prior to the spray dryer, reduced the gas residence time in the dryer and contributed to wet solids build-up on the chamber walls (4). Mikropul consulted with Koch Engineering Co. in late 1979 about modifying the initial dryer design. In early 1980, proprietary spray dryer "internals" were installed to improve the gas/liquid mixing and "changes in the operating procedure" were instituted. No details were reported on the operating procedure changes. The changes, combined with installation of the internals and modification of the feed slurry distribution to the atomizers, were reported to result in the system being on stream 99 percent of the scheduled hours of operation during a 90-day demonstration period.

At the Flakt system located at the Jim Bridger Station, a low inlet gas temperature was reportedly the major cause of wet solids build-up on the walls. In this case, the dryer inlet gas temperature was generally between 210 and 240°F. The low gas temperature limited the drying of the solids. Flakt reports that a 2- to 4-in. thick "self-limiting" layer of solids built up on the walls (8). The accumulated material would periodically collapse off the walls and overload the spray dryer hopper. At other times the reactor would be shut down to remove the deposits. The problem was addressed by modifying the hoppers to handle larger capacities and realigning the nozzle atomizers to prevent moist particles from directly hitting the walls.

At EPRI's Arapahoe plant a relatively low gas residence time of 5 seconds at full gas flow has limited the approach to saturation to 25 to 30°F. Reducing the gas flow to give a 7-second residence time has helped to allow trouble-free operation at a 20°F approach.

No spray dryer operational problems have been reported for the Argonne or Riverside systems. The Argonne system has a 25-ft diameter dryer with a 10-second residence time. The dryer is normally operated at a 22 to 23°F approach to saturation. The 46-ft diameter Riverside dryer has a nominal 10- to 12-second residence time. The dryer is normally operated at either an 18°F or 35°F approach to saturation. Figure 4-3 shows the moisture content of the Riverside spray dryer product as a function of the approach to saturation. This figure shows a moisture content of less than 2 percent at a 20°F approach with fine atomization (no droplet size ranges were given). The Joy/Niro spray dryers at Riverside and Argonne have a central gas disperser. A portion of the total inlet gas flow is ducted through this disperser which discharges below the atomizer inside the spray dryer.

4.4 FABRIC FILTER/ESP DESIGN, OPERATION, AND PERFORMANCE

As discussed in Section 2, the large majority of commercial spray drying systems sold to date use fabric filters for collection of product solids and fly ash. Pulse-jet fabric filters are common for industrial applications, while reverse-air types are used in utility systems. The most important factors in fabric filter design are selection of proper bag fabric, pressure drop characteristics, adequate solids handling capability, and adequate insulation. These factors are related to the low inlet gas temperature for FGD applications, the potential for using the fabric filter even when the spray dryer is off-line, and the higher dust loadings to the fabric filter when the spray dryer is being operated.

Some operating systems do, however, use ESP's. The Flakt system at the Jim Bridger Station operates with the existing ESP. Also, Joy/Niro has operated the Riverside spray dryer with the existing ESP's at that station as well as with the new fabric filter. For ESP's, the important design factors are the higher dust loadings associated with spray dryer operation, the potential need for use of the ESP when the spray dryer is not operating, and the resistivity of the particles to be collected, both with and without the spray dryer in use.

The vendors generally rely on site-specific economics and customer preference in selecting the type of particulate control system for their dry FGD systems.

Table 4-1 shows the available performance data from operating full-scale systems. In general, all the particulate control systems have met or exceeded

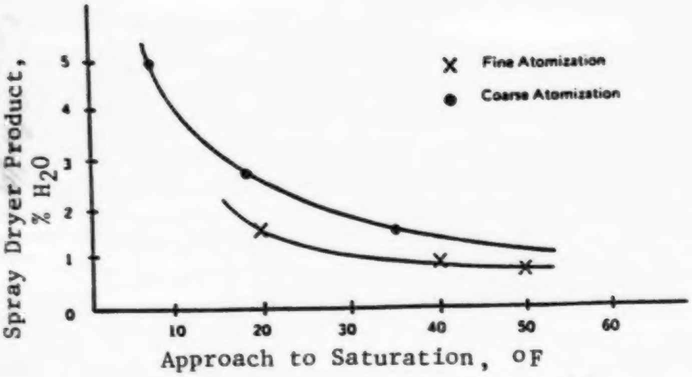


Figure 4-3. Spray dryer product moisture as a function of approach temperature - Riverside.

Source: Reference 9.

TABLE 4-1. RECENT PERFORMANCE DATA FOR SPRAY DRYING SYSTEM FABRIC FILTERS AND ESPs[a]

System/Vendor	Performance Data	Comments[a]
Riverside/Joy-Niro - Fabric filter (Reference 9)	0.003 to 0.006 gr/acf outlet emissions; <5% opacity, without spray dryer; 0.001 to 0.02 gr/acf with spray dryer.[b]	Inlet grain loadings of 4.3 to 12.1 gr/acf with spray dryer operating; 1.2 to 2.9 gr/acf without spray dryer.
Riverside/Joy-Niro -ESP (Reference 9)	95.91 to 99.75% collection efficiency at operating specific collection areas of from 158 to 208 $ft^2/10^3$ acfm.	Specific collection area of 400-600 $ft^2/10^3$ acfm may be required to meet 0.03 lb/10^6 Btu NSPS requirements with the spray dryer in operation.
Argonne/Joy-Niro -Fabric filter (Reference 1)	Boiler Load (%) / Outlet Emissions[c] gr/dscf / lb/10^6 Btu 35 / 0.0057 / 0.016 70 / 0.0039 / 0.010 82 / 0.0021 / 0.005	Total system pressure drop ranged from about 4 in. w.g. at low load to about 10 in. w.g. at 82% boiler load.
Coyote/Rockwell-Wheelabrator-Frye -Fabric filter (Reference 7)	No emissions data reported, but said to have met performance guarantees of 0.1 lb/10^6 Btu outlet emissions.	Low bag failure rate. No corrosion or condensation damage observed in fabric filter (system operates at 50 to 60°F approach to saturation).
Strathmore/Mikropul-Koch - **Fabric filter** (Reference 4)	0.015 lb/10^6 Btu (average of 3 tests) outlet emissions, corresponding to 0.004 gr/acf.	Low bag failure rate. No corrosion or condensation damage observed. Operates at approximately 35 to 40°F approach to saturation.
Jim Bridger/Flakt -ESP (Reference 8)	Final data not available for full-scale system yet. Pilot plant tests showed a 0.01 gr/acf outlet emissions and less than 10% opacity.	Pilot plant ESP removal efficiency was reported to increase from 99.3 to 99.7% when spray dryer operated. Improvement attributed to lowered resistivity due to lower gas temperature, high humidity, and higher alkali content of the dust relative to fly ash alone.

---

[a] Also see text for information about the various systems (Section 4 and vendor write-ups in Section 3).

[b] 0.02 gr/acf measurement attributed to broken bags.

[c] Measured at the fabric filter outlet with the spray dryer in operation.

performance guarantees. Relatively few problems have been encountered in the use of these well-established technologies as part of the FGD system. There are, however, some special considerations. These considerations are related primarily to the low temperature of the gas and higher dust loadings.

Joy/Niro conducted extensive fabric filter tests at the Riverside Station. They installed bags of different fabrics and monitored each of the fabric types. Teflon-coated fiberglass bags exhibited the lowest failure rates. Fiberglass bags with a silicone, graphite, and teflon tri-coated finish exhibited "unacceptable" failure rates. Polyester bags were found unsuitable due to their temperature limitations when subjected to flue gas at 300 to 350°F (10).

Some localized corrosion was observed in the areas of access doors and viewing ports. Corrosion was also observed in compartments that were located adjacent to compartments that were off-line for extended periods of time. Joy/Niro has stressed the importance of adequate insulation in the fabric filter, especially if the dryer is to be operated at a close approach to saturation (18-20°F).

Neither the Coyote, nor the Strathmore systems have reported any design or operating problems with their FGD system fabric filters. Montana-Dakota Utilities reported that from system start-up in November 1981 through April 1982 only 10 of 7,752 fabric filter bags had been replaced, and five of these were damaged during installation (8). Montana-Dakota has indicated that lightweight acrylic and Nomex bags have provided the best service in terms of lowest pressure drop and acceptable bag life. They have also indicated that 7.1-oz acrylic bags are likely to be their final choice.

Mikropul/Koch reported a 5 percent bag replacement rate for the Strathmore system fabric filter in 30 months of service (4). The pulse-jet fabric filter has homopolymer acrylic bags with a proprietary finish.

The Argonne system was shut down in October 1982, after 10 months of operation, for a complete bag replacement. The reported cause was delamination of the woven felt bags (20). The felt bags were replaced with woven fiberglass bags.

4.5 SOLIDS RECYCLE

Solids recycle is an important part of spray dryer system design, not only due to the potential for use of unreacted reagent and fly ash alkalinity to reduce reagent requirements, but also due to operability considerations. Both Joy/Niro results and recent experience at EPRI's Arapahoe pilot plant have indicated that solids recycle, which increases the percent solids in the atomizer feed, improves rotary atomizer operability by reducing plugging and scaling.

Several investigations of the benefits of solids recycle have been covered in previous surveys (11, 12) and other summary reports (13,14,15). The previous studies have been designed to assess the effectiveness of solids recycle in reducing fresh reagent requirements as a function of recycle ratio, recycle addition configuration, and the source of recycle solids (spray dryer or fabric filter). The complete results of previous studies are too lengthy to repeat here, but can generally be summarized as follows:

- Typical recycle ratios range from 1 to 3 lb recycle solids per lb of fresh lime; recycle ratios lower than 1 show little benefit and recycle ratios higher than 3 show no increasing benefit in SO_2 removal. In addition, pumping limitations are approached at very high recycle ratios.
- Recycle has shown anywhere from 0 to 10 percent increase in overall SO_2 removal (e.g., from 60 to 70 percent SO_2 removal) depending on recycle ratio, fly ash alkalinity, utilization of the fresh lime on the first pass through the dryer, and method of adding the recycle solids.
- Three recycle configurations, shown in Figure 4-4, have been investigated in various tests. There is no consensus between vendors as to the favored configuration with respect to increasing SO_2 removal or reducing fresh reagent requirements.
- The source of recycle solids has also been investigated, but again there is no consensus as to whether it is better to recycle from the spray dryer or from the baghouse or whether there is no difference.

New information on solids recycle since the last survey comes from the Argonne system and from the EPA-sponsored pilot program conducted by G.E. Environmental Services.

The Argonne data is shown in Figure 4-5. "External stoichiometry" is defined as:

$$\text{External stoichiometry} = \frac{\text{moles of fresh lime}}{\text{moles of inlet } SO_2} \qquad (4\text{-}1)$$

"Internal stoichiometry" includes the unreacted lime in the recycle solids and is defined as:

$$\text{Internal stoichiometry} = \frac{\text{moles of fresh \& recycle lime}}{\text{moles of inlet } SO_2} \qquad (4\text{-}2)$$

The Argonne system normally operates with about a 2.0 lb recycle/lb fresh lime recycle ratio (16). A typical product solids analysis has been reported as (1):

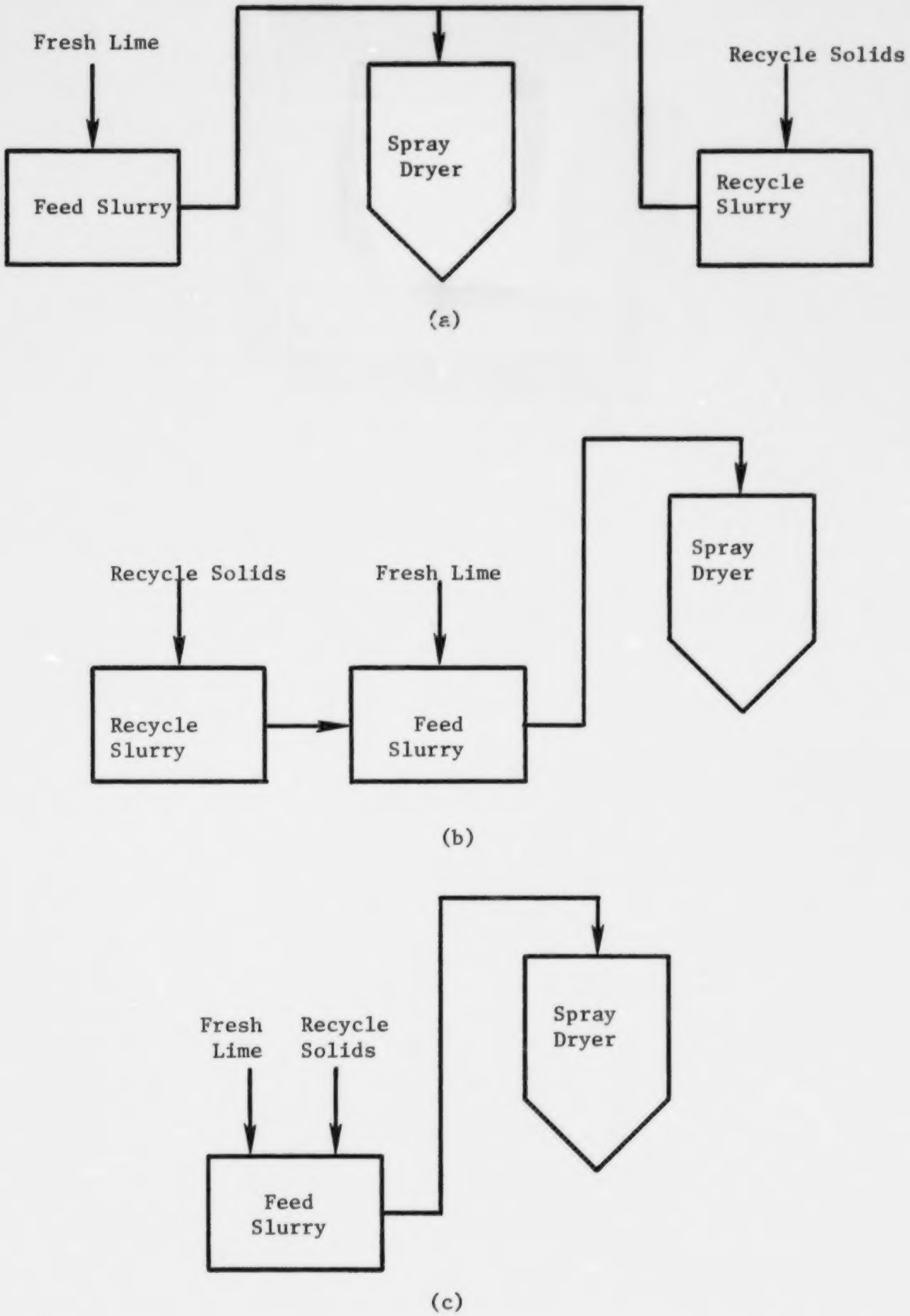

Fresh Lime
Recycle Solids
Feed Slurry
Spray Dryer
Recycle Slurry
(a)
Recycle Solids
Fresh Lime
Spray Dryer
Recycle Slurry
Feed Slurry
(b)
Fresh Lime
Recycle Solids
Spray Dryer
Feed Slurry
(c)

Figure 4-4. Recycle addition configuration alternatives.

Component	Weight %
Moisture	2.4
Al_2O_3	1.15
Fe_2O_3	2.12
SiO_2	2.45
MgO	0.69
Na_2O	0.10
$CaSO_3$	58.8
$CaSO_4$	12.8
$Ca(OH)_2$[asCaO]	6.62
Loss on ignition	12.9

It should be noted that all the calcium is reported as product ($CaSO_3$ or $CaSO_4$) or unreacted lime. No $CaCO_3$ or fly ash calcium value is reported. If CO_2 is absorbed across the dryer or if there is a significant amount of $CaCO_3$ in the fresh lime or calcium in the fly ash, the internal stoichiometry would be lower than shown in Figure 4-5.

Figure 4-5 shows that at 90 percent SO_2 removal, the external stoichiometry is about 1.4, while the internal stoichiometry is about 2.2. These data do not, however, indicate the effectiveness of recycle for these particular conditions since no corresponding once-through (no recycle) data are available for comparison.

In the EPA-funded program conducted by G.E. Environmental Services at the City of Colorado Springs' Martin Drake Station, fly ash from high sulfur eastern coal-fired boilers was injected into the duct just upstream of the spray dryer. The spray dryer was operated in both once-through and solids recycle modes (17). The purpose of the tests was to investigate the effects of the fly ash from eastern coal at inlet SO_2 concentrations of 1500 to 4000 ppmv. The Martin Drake boiler burns a low sulfur western coal which produces 300 to 600 ppm inlet SO_2. Desired SO_2 levels were obtained by spiking the flue gas. The fly ash from the Martin Drake boiler, which was not removed before the spray dryer, is fairly alkaline. Compositions of the Martin Drake fly ash and the eastern coal ashes are shown in Table 4-2. Table 4-3 shows the results of the tests conducted.

Figure 4-6 shows the results of once-through and recycle tests with the injected ash compared to design curves developed by G.E. Environmental Services in previous Martin Drake testing (6). The data indicate that overall system SO_2 removal is improved under both once-through and recycle at a reagent ratio of 1.2 and under recycle conditions at 1.55 and 1.7 reagent ratios. Little or no improvement was seen in once-through operation at the higher reagent ratios and inlet SO_2 concentrations (1.55 to 1.7 reagent ratio and 3000 to 4000 ppmv inlet SO_2). G.E. Environmental has attributed the improvement in SO_2 removal under recycle conditions to the acidic nature of the injected eastern coal fly ash, theorizing that it may promote dissolution of $CaCO_3$ in the recycle solids (18). G. E. has stated that the recycle solids contained 10 to 11 percent $CaCO_3$, although data were not available on

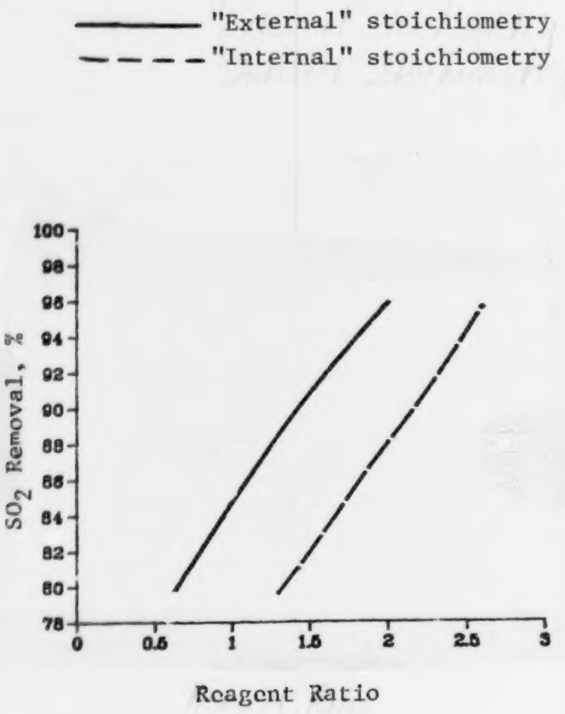


Figure 4-5. SO_2 removal as a function of reagent ratio - Argonne System.

Notes: Recycle ratio is about 2 lb/lb fresh lime.
Tests conducted at about 2200 ppm inlet SO_2, 23°F approach
See text for definition of "external" and "internal" stoichiometry. (Reference 1).

TABLE 4-2. COMPOSITION OF FLY ASHES IN MARTIN DRAKE TESTS[a] (17)

Quantity	Eastern Stoker Ash[b]	Eastern Tangential Ash[b]	Eastern Cyclone Ash[b]	Martin Drake Ash
SiO_2	34.0	45.8	28.0	62.4
Al_2O_3	14.3	19.3	13.5	23.2
CaO	2.2	2.05	1.5	3.15
Fe_2O_3	23.6	26.0	21.0	3.7
Na_2O	0.49	0.41	0.31	0.21
K_2O	1.9	2.0	1.75	1.2
MgO	1.2	0.90	0.69	1.3
P_2O_5	0.38	0.16	0.24	1.2
SO_3	1.1	0.45	0.53	0.45
Loss on ignition	19.4	1.4	31.3	1.85
Alkalinity (meq/gm)	-0.062[c]	-0.038[c]	-0.037[c]	0.180
Concentration at spray dryer inlet (gr/acf)	2.5	2.0	1.0	1.8

[a] All compositions in weight percent.

[b] Fly ash from stoker-fired, tangentially fired and cyclone-fired boilers burning high sulfur eastern coals.

[c] Negative alkalinity indicates acidic fly ash.

TABLE 4-3. DEPENDENCE OF SO_2 REMOVAL IN SPRAY DRYER/BAGHOUSE COMBINATION ON INJECTED FLY ASH CHARACTERISTICS AT INLET SO_2 CONCENTRATIONS TYPICAL OF HIGH SULFUR COAL.[a]

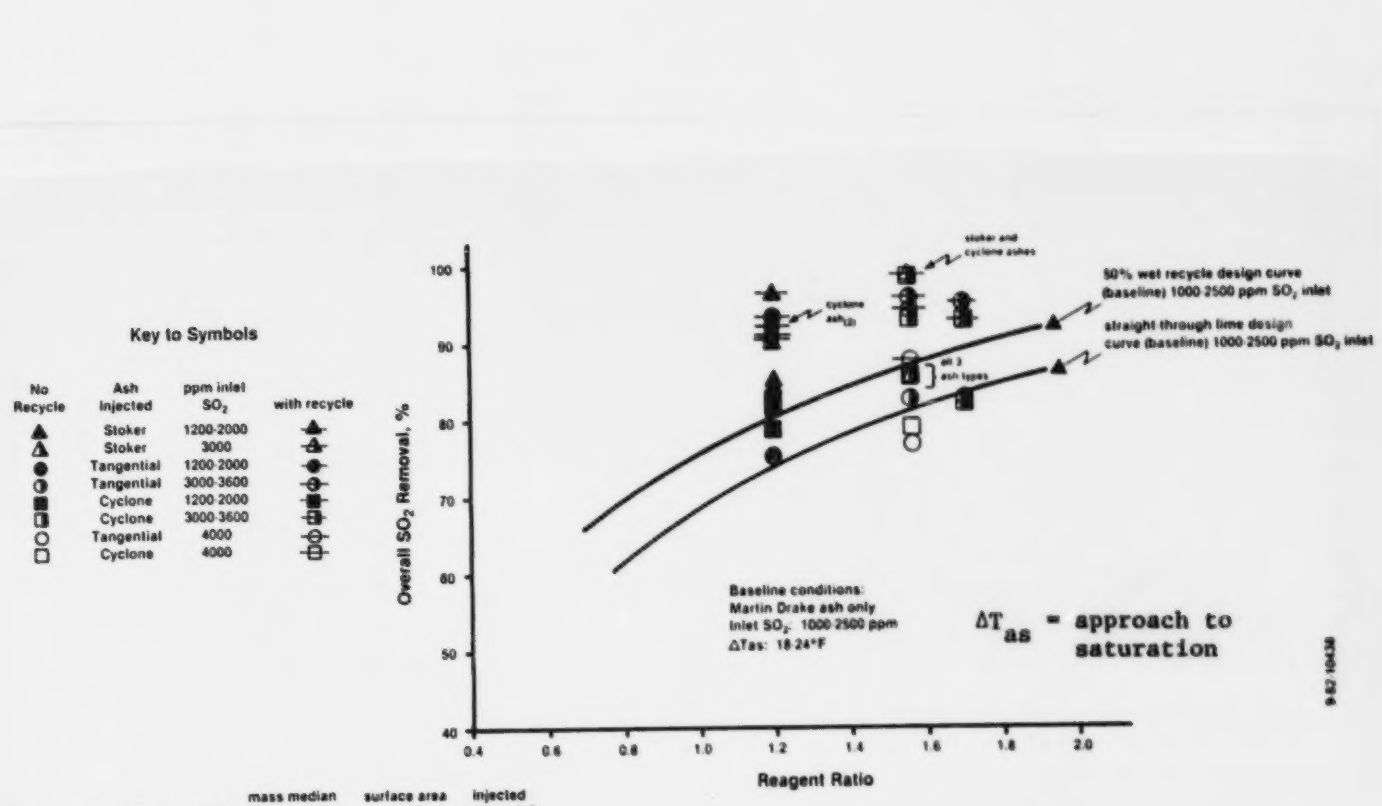
Inlet SO_2, ppm	Stoichiometric ratio	50 percent wet recycle	Efficiency of SO_2 Removal in spray dryer, percent			Efficiency of SO_2 removal in baghouse, percent			Overall SO_2 removal efficiency in spray dryer/baghouse combination, percent		
			Stoker[b]	Tangential[c]	Cyclone[d]	Stoker[b]	Tangential[c]	Cyclone[d]	Stoker[b]	Tangential[c]	Cyclone[d]
1200	1.20	No	74.7	75.9	72.6	38.3	32.0	21.5	84.4	83.6	78.5
		Yes	86.6	84.8	83.7	74.6	57.2	47.9	96.6	93.5	91.5
2000	1.20	No	75.4	69.3	71.3	33.3	22.1	34.8	83.7	76.1	81.3
		Yes	87.4	84.3	81.9	23.0	44.6	47.5	90.3	91.3	90.5
3000	1.55	No	77.1	76.7	86.4	39.3	37.8	50.0	86.1	85.5	93.2
		Yes	87.2	87.0	91.6	85.9	60.8	85.7	98.2	94.9	98.0
3600	1.70	No		72.6	74.8		34.7	29.4		82.1	82.2
		Yes		85.3	83.7		56.5	53.4		93.6	92.4
4000	1.55	No		69.1	68.9		23.3	29.3		76.3	78.0
		Yes		78.6	77.7		39.3	32.7		87.0	85.0

[a] All tests were conducted for a spray dryer inlet flow rate of 8500 cfm at 325°F and a 20°F approach to saturation.

[b] Refers to stoker-fired boiler fly ash being injected to obtain a concentration of 2.5 gr/ft^3 at dryer inlet.

[c] Refers to tangentially fired boiler fly ash being injected to obtain a concentration of 2.0 gr/ft^3 at dryer inlet.

[d] Refers to cyclone-fired boiler fly ash being injected to obtain a concentration of 1.0 gr/ft^3 at dryer inlet.



No Recycle	Ash Injected	ppm inlet SO_2	with recycle
▲	Stoker	1200-2000	-▲-
△	Stoker	3000	-△-
●	Tangential	1200-2000	-●-
◐	Tangential	3000-3600	-◐-
■	Cyclone	1200-2000	-■-
◧	Cyclone	3000-3600	-◧-
○	Tangential	4000	-○-
□	Cyclone	4000	-□-

Ash	%Si	$\%Fe_2O_3$	LOI	mass median diameter, μm	surface area $\mu m^2/g$	injected conc. gr/ft^3
Stoker	34	23.6	19.4	67	1060	2.5
Tangential	46	26.0	1.4	28.5	2510	2.0
Cyclone	28	21.0	31.3	14.3	2530	1.0
Martin Drake (baseline)	62.4	3.7	1.85	17.3	2800	1.8

Figure 4-6. Recycle and once-through results comparison.

how much of the $CaCO_3$ was associated with the fresh lime and how much was attributable to CO_2 absorption across the dryer (19). G. E. Environmental has also offered the following theories on the observed SO_2 removal enhancement with injected eastern coal fly ash (17):

- The acidic hydrolysis of eastern coal fly ash promotes lime dissolution, similar to the mechanisms by which adipic acid can enhance lime dissolution.
- The acidity of the fly ash promotes "clearing of the pores" in the product solid particles, allowing better access of the SO_2 to unreacted lime at the center of the particle.
- The acidic eastern fly ash has more affinity for lime than neutral or alkaline ash and the surface area available for reaction is increased as the lime coats the surface of the fly ash.
- The fly ash acts as a catalyst for SO_2 oxidation and thus enhances the reactivity of the lime with SO_2.

Further research on the effects of eastern fly ash and the mechanisms by which it may enhance SO_2 removal are being conducted by G.E. Environmental under EPA funding.

4.6 PERFORMANCE DATA

Since the last survey, performance data from several systems have been published. Much of the data is from performance or compliance testing conducted before the system was accepted by the purchaser. Table 4-4 provides a summary of recently published performance test data.

Figure 4-7 shows recently published data on SO_2 removal as a function of reagent ratio for several different lime-based systems. Test conditions for the data presented are listed in the accompanying Table 4-5.

Data from EPA-funded pilot-scale tests at Comanche and Martin Drake are shown in Figures 4-8 and 4-9 for comparison.

TABLE 4-4. PERFORMANCE AND COMPLIANCE TEST DATA FOR SPRAY DRYING SYSTEMS

System/Vendor	Performance/Compliance Test Data				Comments
Argonne Labs/Joy-Niro (Reference 1)	Boiler Load (% MCR)[a]	Inlet SO_2 (lb/10^6 Btu)	Outlet SO_2 (lb/10^6 Btu)	SO_2 Removal (%)	Lime reagent, solids recycle, 3% S coal, EPA Method 6 tests.
	35	6.69	1.36	79.7	
	70	5.93	0.60	89.9	
	82	6.13	0.27	95.6	
Strathmore/Mikropul-Koch (Reference 4)	Test #	Inlet SO_2 (ppmv)	Outlet SO_2 (ppmv)	SO_2 Removal (%)	Lime reagent, no solids recycle, 3.79% S coal. EPA Method 6 tests. About 75% boiler load for all tests.
	1	2057	132	93.6	
	2	1948	65	96.7	
	3	2014	195	90.3	
	4	1974	166	91.6	
	5	1984	196	90.1	
	6	2016	156	92.3	
	avg.			92.4	
Jim Bridger/Flakt (Reference 8)	Reagent	SO_2 Removal (%)		Guarantee Removal (%)	EPA Method 6 tests, about 0.6% S coal.
	Soda ash	88.3		86.5	
	Lime with recycle	90.8		74	
	Lime with no recycle	64.1		62	
Coyote/Rockwell-Wheelabrator-Frye (Reference 7)	Met performance guarantee of 70% SO_2 removal at 75% reagent utilization.				Soda ash reagent. Recent data showed 70% removal at reagent utilizations of 95% or greater.

---

[a] MCR - maximum rated capacity.

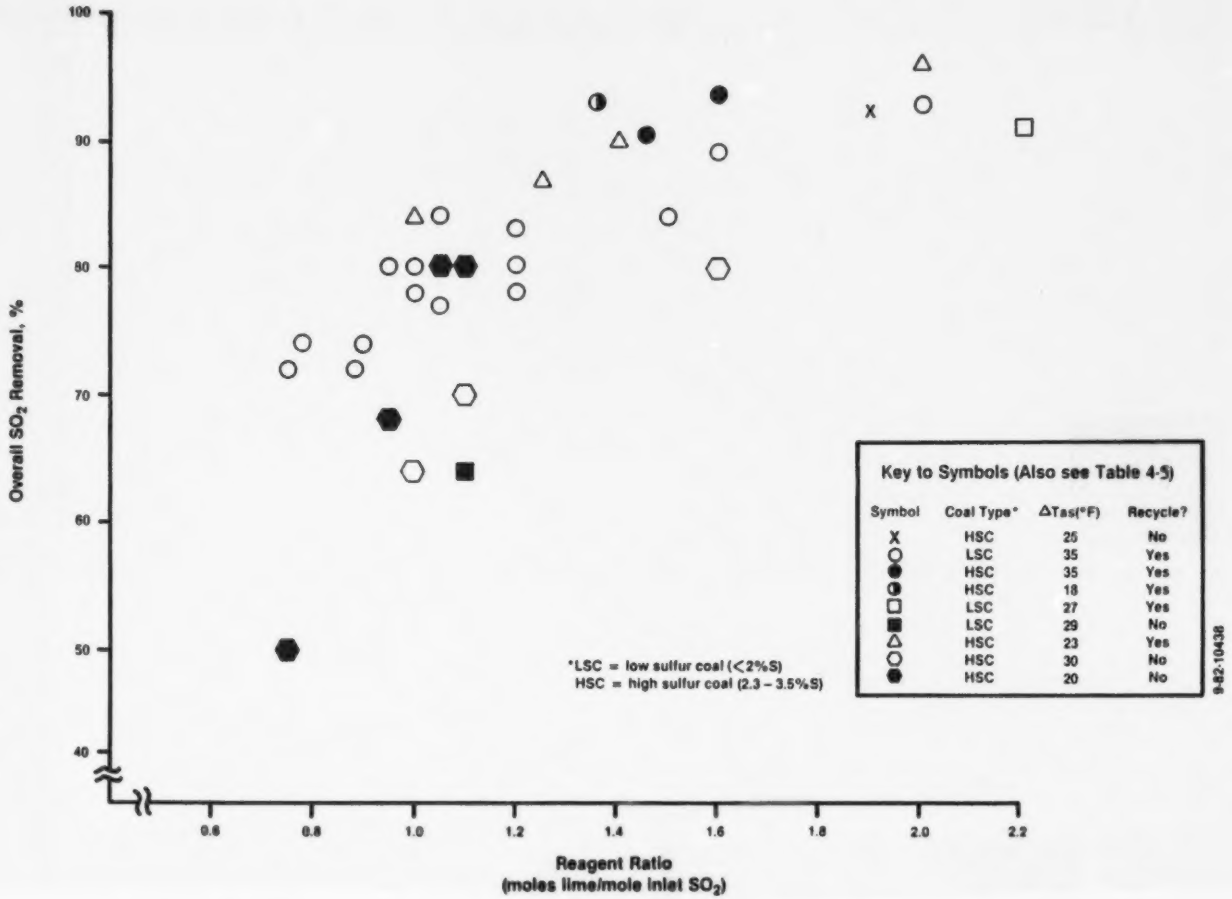


Figure 4-7. Comparison of overall SO$_2$ removal data for various lime-based spray dryer FGD systems.

4-5

4-7

TABLE 4-5. PROCESS CONDITIONS FOR DATA SHOWN IN FIGURE 4-7.

Symbol from Figure 4-7	System Description[a]	Coal Type	%S	Process Conditions Inlet SO_2 (ppmv)[c]	Inlet Gas Temp. (°F)	ΔT (°F)[d]	Recycle
○	Riverside Station: 110 MWe unit; 680,000 acfm; 46-ft diameter dryer; rotary atomizer; fabric filter	Colstrip coal blended with petroleum coke	1.2	850-1000	280-315	35	Yes
●	Riverside	Illinois bituminous	3.5	~2000	316-331	32-35	Yes
◑	Riverside	Illinois bituminous	3.5	~2000	~315	18	Yes
□	Jim Bridger Station; 100 MWe unit; 389,000 acfm; ten dual-fluid nozzle atomizers; ESP	Western sub-bituminous	~0.6	NR	229	27	Yes
■	Jim Bridger	Western sub-bituminous	~0.6	NR	238	29	No
x	Strathmore: 85,000 lb steam/hr; 40,000 acfm; 14.5-ft diameter dryer; rotary atomizer; fabric filter	Eastern bituminous	3.8	~2000	~330	25	No
△	Argonne Labs: 170,000 lb steam/hr boiler; 75,000 acfm; 25-ft diameter dryer; nozzle atomizers; fabric filter.	Illinois bituminous	3.0	~2200	~300	23	Yes
⬡	PETC: 500 lb/hr pulverized coal furnace; 7-ft diameter dryer; rotary atomizer; fabric filter	West Virginia bituminous	3.1	~2200	~400	30	No
⬢	PETC	West Virginia bituminous	3.1	NR	NR	20	No

[a] Riverside system is a Joy/Niro design. See Section 3-13.
Jim Bridger system is a Flakt design. See Section 3-11.
Argonne system is a Niro/Joy design. See Section 3-13 .
See Section 3-6 for description of PETC system.

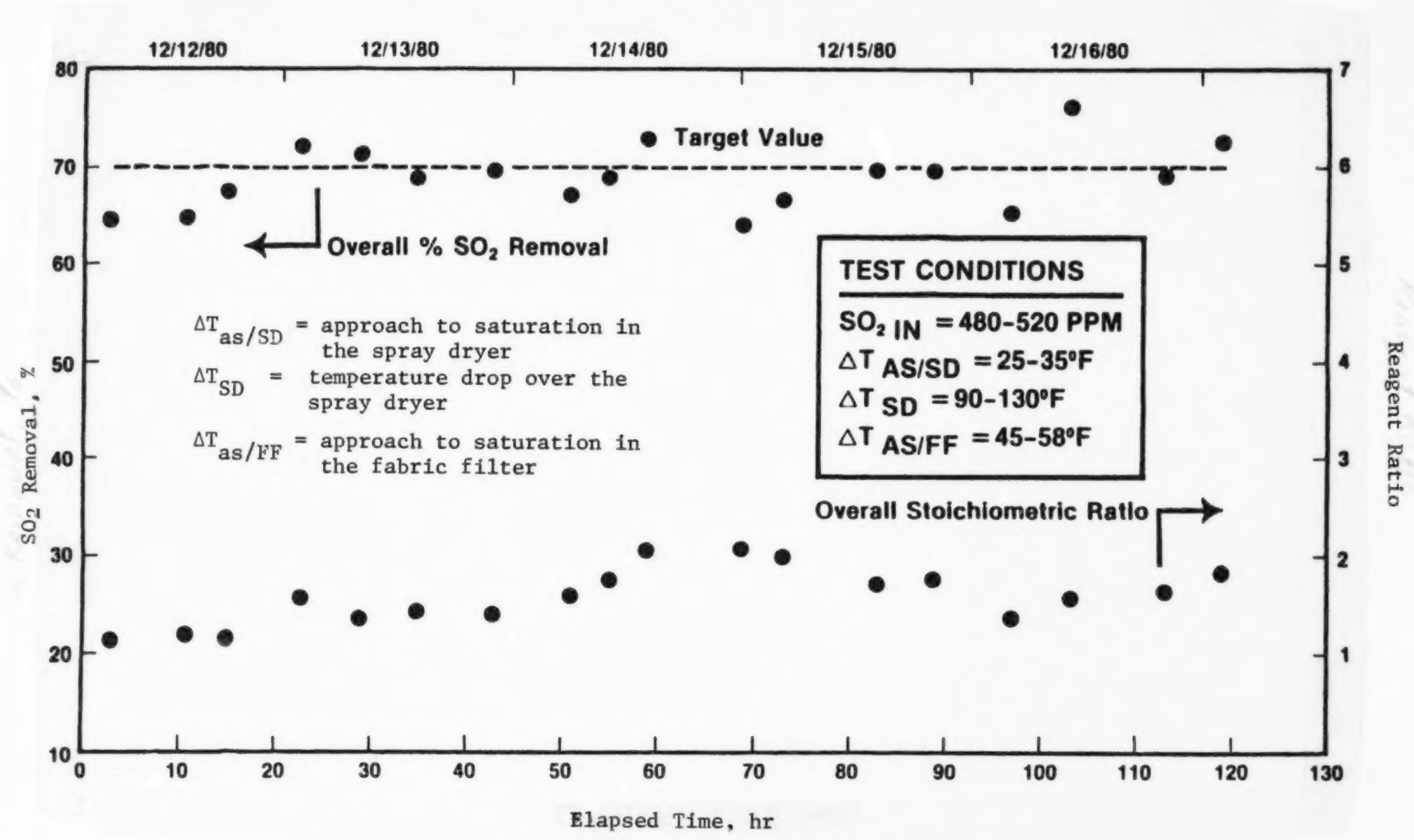


Figure 4-8. SO_2 removal versus reagent ratio data - Comanche.
Source: Reference 5.

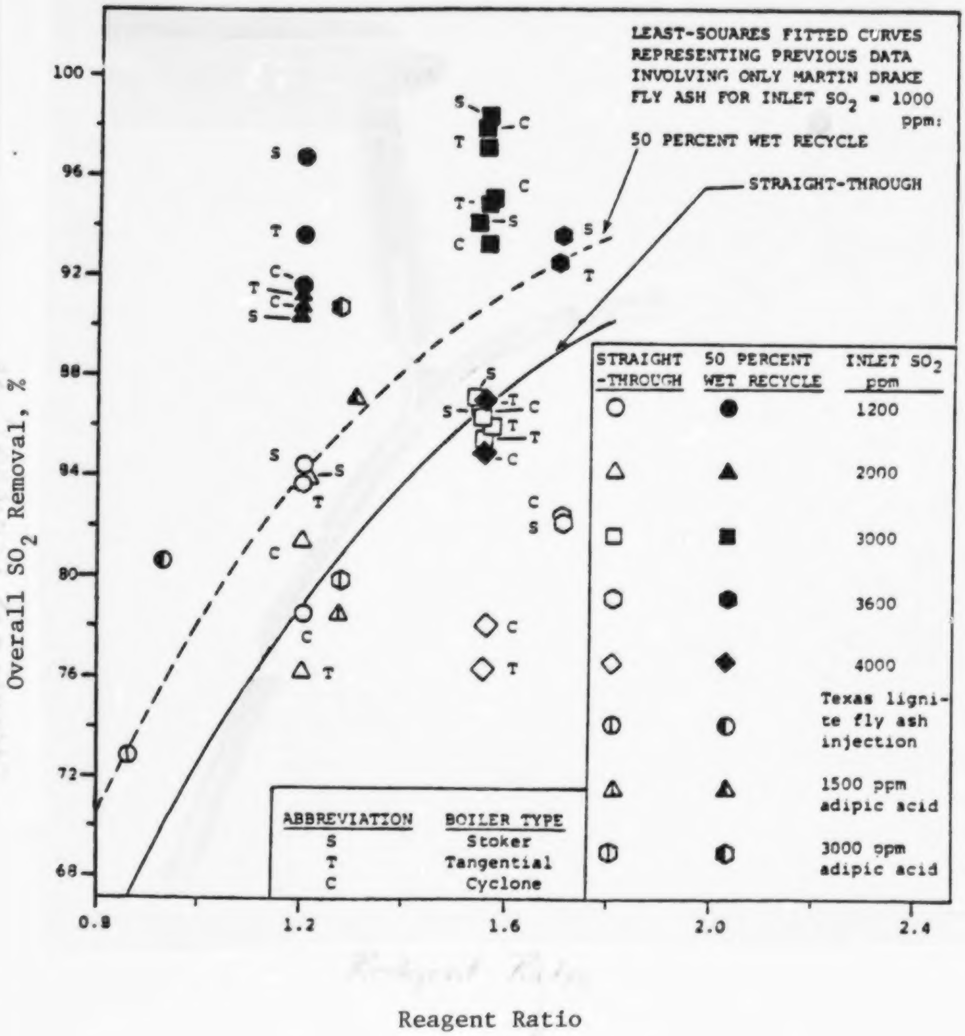


Figure 4-9. SO_2 removal vs. reagent ratio - Martin Drake.
Source: Reference 17.

4.7 REFERENCES

1. Farber, Paul S. "Start-up and Performance of a High Sulfur Dry Scrubber System." (Presented at the 75th Annual Meeting of the Air Pollution Control Association, New Orleans, Louisiana, June 20-25, 1982, Paper #82-40.5.)

2. Spencer, Bert, Joy Equipment Company-Western Precipitation Division. Telephone conversaiton with M. E. Kelly, Radian Corporation, March 19, 1982.

3. Buschmann, John C. and Robert C. Hyde. "Corrosion - Problems and Solutions." (Presented at the Joy/Niro Seminar, Minneapolis, Minnesota, June 26-27, 1982.)

4. Reinauer, T. V., J. P. Monat, and M. Mutsakis. "Dry FGD on an Industrial Boiler: 20,000 Hours of Operating Experience." (Presented at the 79th Annual AIChE Meeting, Cleveland, Ohio, August 29-September 1, 1982.)

5. Stevens, N. J., et al. *Dry SO_2 Scrubbing Test Program*. Final Report, EPA Contract No. 68-02-3190. U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, October 1982.

6. Parsons, Edward L., et al. "SO_2 Removal by Dry FGD." In: *Proceedings of Symposium on Flue Gas Desulfurization-Houston, October 1980*; Volume 2. EPA-600/9-81-019b, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, April 1981, p. 818.

7. Lewis, M. F. and D. C. Gehri. "Atomization - The Key to Dry Scrubbing at the Coyote Station." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20, 1982.)

8. Farrington, James, Flakt, Inc. Private communication with M.A. Palazzolo, Radian Corporation, August 16, 1982.

9. Meyler, J. A. and Karsten Felsvang. "One Year of Operation of the Riverside Dry Scrubber." (Presented at the 44th American Power Conference, Chicago, Illinois, April 26-28, 1982.)

10. Spencer, H. W., Y. J. Chen, and M. T. Quack. "Results of Baghouse and Fabric Testing at Riverside." (Presented at the Joy/Niro Seminar, Minneapolis, Minnesota, June 26-27, 1982.)

11. Kelly, M. E. and S. A. Shareef. *Second Survey of Dry SO_2 Control Systems*. EPA-600/7-81-018. U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, October 15, 1980.

12. Kelly, M. E. and S. A. Shareef. *Third Survey of Dry SO_2 Control Systems*. EPA-600/7-81-097, NTIS PB 81-218976. U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, June 1981.

13. Ireland, P. A. *Status of Spray Dryer Flue Gas Desulfurization*. Final Report EPRI CS-2209. Electric Power Research Institute, Palo Alto, California, January, 1982.

14. Apple, Cathy and Mary E. Kelly. *Mechanisms of Dry SO_2 Control Processes*. EPA-600/7-82-026, NTIS PB-82196924, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, April 1982.

15. Brna, Theodore G., U.S. Environmental Protection Agency. Private communication with M.E. Kelly, Radian Corporation, March 1982.

16. Palazzolo, M. A. Trip Report: Visit to Argonne Labs Spray Dryer FGD System. Radian Corporation, Durham, North Carolina, July 22, 1982.

17. Samuel, Eric A., et al. "Dry FGD Pilot Plant Results: Lime Spray Absorption for High Sulfur Coal and Dry Injection of Sodium Compounds for Low Sulfur Coal." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20, 1982.)

18. Samuel, Eric A., General Electic Environmental Services, Inc. Presentation to 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 20, 1982.

19. Samuel, Eric A., General Electric Environmental Services, Inc. Telephone conversation with M. E. Kelly, Radian Corporation, June 1982.

20. Brna, Theodore G., U.S. Environmental Protection Agency. Telephone conversation with M. E. Kelly, Radian Corporation, January 12, 1983.

SECTION 5

DRY FGD WASTE DISPOSAL

The collective experience of the U. S. utilities and industries in operating wet scrubbers and disposing of scrubber waste (sludge, fly ash) has been studied and documented fairly extensively. Studies have been aimed at (1) developing a data base on sludge and ash handling procedures, (2) providing independent evaluations of the sludge fixation processes, (3) quantifying variables affecting the solubility of trace elements and potentially toxic species from solid waste by-products, and (4) establishing guidelines for the construction of sludge disposal facilities.

Similar efforts directed at characterization, disposal, and utilization of waste from dry SO_2 control systems are now well underway. Studies conducted in the last 2 years have generated a substantial data base on the chemical and physical characteristics of dry FGD wastes. As more commercial dry FGD systems begin to operate, an even broader data base should emerge. This section presents some of the findings of recent research work in the area of dry FGD waste characterization. The current and planned disposal methods for the commercial dry FGD systems sold to date are also presented.

5.1 PHYSICAL AND CHEMICAL CHARACTERISTICS

Under the Resource Conservation and Recovery Act (RCRA), solid waste is defined as "any garbage, refuse, sludge from a waste water treatment plant, water supply treatment plant, or air pollution control facility . . . ." The RCRA further defines a hazardous waste as any solid waste not excluded under Section 261.4 of RCRA. Among these excluded wastes are fly ash, bottom ash, slag, and FGD waste from coal burning sources. If not specifically excluded, then hazardous wastes are either listed in Subpart D, contain chemicals listed in Subpart D, or exhibit hazardous characteristics. Dry FGD waste is not listed in Subpart D and does not contain chemicals listed in Subpart D or exhibit any hazardous characteristics. (The hazardous characteristics mentioned under the law are ignitability, corrosibility, reactivity, and toxicity). Results from several previous studies to characterize dry FGD wastes were presented in the Third Survey of Dry SO_2 Control Systems (EPA-600/7-81-097). Summarized below are the results of more recent studies.

(a) In an EPA-sponsored study, Cottrell Environmental Sciences, Inc. evaluated the characteristics of lime-based spray dryer waste generated at Public Service Company of Colorado's Comanche Station (1). The Comanche fly ash is highly cementitious and has a high reactive CaO content. Properties measured included compacted density, triaxial compression, permeability, and leachate composition.

Optimum compacted densities in the range of 78 to 90 lb/ft^3 were obtained with moisture contents in the range of 25 to 30 percent by weight. The compacted densities for the dry scrubbing wastes were lower than for sludge/fly ash blends from wet FGD systems measured by Cottrell in previous studies.

Triaxial compression test results showed that the cohesive strength and angle of internal friction of products from straight-through operation to be greater than that for products from operation with solids recycle. The greater amount of unreacted lime in the products from straight-through operation may have caused the increase in cohesive strength.

Permeability measurements for waste solids from the Comanche pilot plant ranged from 10^{-4} to 10^{-6} cm/sec for cured and uncured samples. Permeability generally decreased after curing.

Leachate tests showed that total dissolved solids (TDS) generally exceeded 1200 ppm. The bulk of the dissolved solids was $CaSO_4$.

(b) Niro Atomizer has recently evaluated physical and chemical characteristics of waste solids generated at their Riverside spray dryer demonstration facility (2). FGD waste solid and fly ash samples were collected when three different coals were fired in the boilers. The fuels included:

- low sulfur subbituminous coal plus petroleum coke (∿1.2% S),
- high sulfur bituminous coal (∿3.5% S), and
- low sulfur subbituminous coal (∿0.8% S).

Solid waste compositions, extract compositions, compressive strengths, permeability coefficients, and optimum moisture contents were determined. In addition, other tests were conducted to investigate ocean disposal of compressed waste products and the production of briquettes and synthetic aggregate (pellets) from the waste products.

The results of solid chemical composition analyses showed that the low sulfur fly ashes had higher calcium contents than the high sulfur ash. This calcium can reportedly be utilized for SO_2 absorption in the spray dryer if solids recycle is used.

The results of moisture-density tests are shown in Table 5-1. As shown in Table 5-1, optimum moisture content varies from one fly ash to another and the product optimum moisture is higher than for the fly ash. It should be noted that the low sulfur product sample was inadvertently collected under non-representative operating conditions. When the sample was collected, the unit was operating

TABLE 5-1. FLY ASH AND SPRAY DRYER PRODUCT MOISTURE-DENSITY RESULTS

Fuel Fired/ Waste Sample	Added Moisture (%)	Dry Density (g/cc)	Optimum Moisture (%)	Maximum Dry Density (g/cc)
Low Sulfur Blend[a]/				
Fly Ash	28	1.28		
	29	1.30	29	1.30
	30	1.29		
Product[b]	33	1.12		
	35	1.24	35	1.24
	37	1.21		
High Sulfur Coal/				
FGD Product[b]	42	1.12		
	43	1.13	43.4	1.13
	44	1.13		
	45	1.12		
Low Sulfur Coal/				
Fly Ash	22	1.40		
	23	1.41	23.5	1.41
	24	1.41		
	25	1.40		
FGD product[b]	26	1.37		
	27	1.38		
	28	1.40	28	1.40
	29	1.38		

[a] Blend of low sulfur coal and petroleum coke.

[b] Waste solids from spray dryer FGD system.

Source: Reference 2.

at low load and a high approach to saturation, resulting in low calcium utilization.

Permeability coefficients for the fly ash and waste products were on the order of 10^{-6} cm/sec. The sample collected at a high approach to saturation showed a permiability of 8.4×10^{-6} cm/sec.

The results of leachate tests on both the fly ash and the dry FGD products showed trace element concentrations one or two orders of magnitude lower than the EPA limits. The leachate would therefore be classified as non-toxic under RCRA regulations.

In tests to investigate end uses of dry FGD products, Niro pelletized the waste solids from tests where the low sulfur blend fuel was fired. The solids were pelletized in both a laboratory mill and in commercial-sized pellet mill. Niro estimated that the cost of pelletizing the FGD product was approximately $5.50/ton. Tests on the compressive strength of the pellets showed that they can be used to produce a synthetic aggregate for use in road base composition.

Niro is currently investigating ocean reef disposal of the waste products as well as the production of briquettes from the waste. Niro has found that the briquettes have adequate strength for handling but cannot be used as synthetic gravel. Results from the reef disposal studies have not been reported yet.

(c) Under contract to EPRI, Radian Corporation measured disposal-related characteristics of 18 different samples of dry FGD waste solids (3). The 18 samples represented waste from nine different test facilities and 14 sets of test conditions. Process operating conditions at the time samples were collected (as reported by the sample suppliers) are given in Tables 5-2 and 5-3.

Most samples were from spray dryer test facilities burning low sulfur subbituminous coal from Wyoming or Montana. Lime was the scrubbing reagent in most cases. Samples from facilities burning low sulfur coals from Colorado, New Mexico, and Pennsylvania, a dry injection system using nahcolite, and from spray dryer systems using sodium carbonate and dolomite as reagents were also analyzed.

A summary of the tests and test procedures used to characterize the waste samples is given in Table 5-4. Most of the waste products were found to have acceptable compressive strengths when enough water was added. Samples from systems using soda ash or nahcolite generally exhibited the lowest strengths. Material collected from fabric filter hoppers exhibited more strength than material from spray dryer hoppers because of the smaller particles in the fabric filter solids. Minimum amounts of water required to obtain

Table 5-2. DESCRIPTION OF POWER STATION UNITS AND OPERATING CONDITIONS DURING SAMPLE COLLECTION FOR DRY SCRUBBING SYSTEMS OPERATED WITHOUT RECYCLE

	STATION AND VENDOR						
	Cameo[a] KVB	Comanche Research-Cottrell	Four Corners Lodge-Cottrell	Jim Bridger Flakt	Joliet Rockwell	Strathmore[h] MikroPul	Strathmore[h] MikroPul
General Specifications of Unit							
Date	11-80	12-79 to 09-80	5-5-81	2-16-81	4-29-81	6-10-81	5-14-81
Boiler Load (MW)	25	NR[b]	650	450	285	~6.5[c]	~6.1[d]
Flue Gas Flow Rate to Dry Scrubber	170,000 acfm	NR[b]	4,600 acfm	15,000 acfm	2,300 acfm	31,000 acfm	NR[b]
Grain Loading (gr/acf)	2	1.5 to 2	3	NR[b]	2	NR[b]	NR[b]
Spray Dryer Conditions							
Alkali Reagent	Nahcolite	Lime	Sodium Carbonate	Hydrated Lime	Lime	Lime	Dolomite
Reagent Feed Rate	1,100 lb/hr of 19.6% Na	0.3 to 0.9 gpm 17 wt. %	1 gpm of 7.1 wt. %	68 lb/hr	4.7 lb/min of 6.8 wt. %	8.4 gpm of 14 wt. %	8.9 gpm
Sample Collection Points	Baghouse/ Ash Pit[e]	Spray Dryer and Baghouse	Spray Dryer and Baghouse	Spray Dryer and Baghouse[f]	Baghouse	Spray Dryer and Baghouse[g]	Baghouse
Percent Fly Ash (wt. %)	50	20 to 35	80	NR[b]	50	NR[b]	NR[b]
Temperature of Flue Gas							
Spray Dryer Inlet (°F)	300	220 to 270	320	234	369	350	313
Spray Dryer Outlet (°F)		130 to 145	140	158	183	175	155
Adiabatic Saturation (°F)	NR[b]	NR[b]	128	131	125	NR[b]	NR[b]
Baghouse or ESP Outlet (°F)	300	150 to 170	140	148	176	172	158
SO_2 Concentrations							
Spray Dryer Inlet (ppm)	350	NR[b]	850	460	1,000	1,100	1,170
Baghouse or ESP Outlet (ppm)	140	35 to 160	33	130	200	270	410
Reagent Ratio $\left(\frac{\text{moles reagent}}{\text{mole inlet } SO_2}\right)$	1	2 to 6	1.1	1.5	1.3	NR[b]	NR[b]
By-Pass (%)	0	15 ± 1	0	NR[b]	0	NR[b]	NR[b]

---

[a] Cameo test facility (on one of those listed here) employed dry injection of nahcolite; thus, "spray dryer" inlet corresponds to nahcolite injection site here.

[b] NR - Not reported.

[c] Strathmore is a steam-generating system having a boiler capacity during the 6-10-81 sampling period of 68,000 lb steam/hr. To provide a basis for comparison to utility boilers, the estimated MW equivalent value was calculated using 1,000 btu/lb and 10,500 btu kWh.

[d] The actual load when the 5-14-81 sample was collected was reported as 64,000 lb steam/hr. The MW equivalent was calculated using assumptions in footnote "c" above.

[e] Cameo sample was collected from ash pit and may not be representative.

[f] Mixed sample tested contained 50 percent product from spray dryer and 50 percent product from baghouse hopper.

[g] Mixed sample tested contained 95 percent product from baghouse and 5 percent product from spray dryer.

[h] All systems in table except Strathmore are pilot or demonstration systems. Strathmore is a commercial unit.

Source: Reference 3.

TABLE 5-3. DESCRIPTION OF POWER STATION UNITS AND OPERATING CONDITIONS DURING SAMPLE COLLECTION FOR DRY SCRUBBING SYSTEMS EMPLOYING LIME ADDITION AND RECYCLE[d]

	STATION AND VENDOR						
	Comanche Research-Cottrell	Joliet Rockwell	Joliet Rockwell	Joliet Rockwell	Martin Drake General Electric	Riverside Joy/Niro	Sherburne County Rockwell
General Specifications of Unit							
Date	12-12-80	4-20-81	4-30-81	5-5-81	2-19-81	7-30-81	6-21-79
Boiler Load (MW)	NA[a]	285	285	285	78	100	640
Flue Gas Flow Rate to Dry Scrubber	4,800 acfm	2,300 acfm	2,300 acfm	2,300 acfm	8,600 acfm	490,000 acfm	2,500 acfm
Grain Loading (gr/acf)	1.5	2	2	2	2.8 gr/acf	2 gr/acf	NR[b]
Spray Dryer Conditions							
Reagent Feed Rate	0.4 gpm of 35 wt. %	3 lb/min of 45 wt. %	4.4 lb/min of 44 wt. %	3.9 lb/min of 45 wt. %	NR[b]	35 wt. %	0.5 gpm of 5.5 wt. %
Recycle Rate $\left(\frac{\text{lb recycled}}{\text{lb fresh feed}}\right)$	2	9	9.4	11.5	NR[b]	NR[b]	5
Sample Collection Points	Spray Dryer and Baghouse	Baghouse	Baghouse	Baghouse	Mixed[c]	Baghouse	Baghouse
Percent Fly Ash (wt. %)	30	50	50	50	NR[b]	60	50
Temperature of Flue Gas							
Spray Dryer Inlet (°F)	271	335	315	267	269	310	261
Spray Dryer Outlet (°F)	148	163	142	146	NR[b]	144	134
Adiabatic Saturation (°F)	113	122	122	122	NR[b]	126	116
Baghouse or ESP Outlet (°F)	175	151	134	172	NR[b]	122	134
SO_2 Concentrations							
Spray Dryer Inlet (ppm)	500	600	1,000	640	524	800	573
Baghouse or ESP Outlet (ppm)	150	90	200	140	94	80	19
Reagent Ratio $\left(\frac{\text{moles reagent}}{\text{mole inlet } SO_2}\right)$	1.6	0.9	0.7	0.8	NR[b]	NR[b]	1.04
By-Pass (%)	19	0	0	16	NR[b]	0	2

[a] NA = No actual value of the boiler load was reported; the boiler load was reported to have run from medium high to medium low values during the sample collection period.

[b] NR = Not reported.

[c] Mixed sample contains 75 percent spray dryer product and 25 percent baghouse product.

[d] All systems in table are pilot or demonstration systems.

Source: Reference 3.

TABLE 5-4. SUMMARY OF TESTS AND TEST PROCEDURES

Parameter	Procedure
Particle Morphology	Scanning Electron Microscope
Chemical Composition of Solids	
Elemental Composition	Inductively Coupled Argon Plasma Emission Spectrometry and Atomic Absorption Spectrophotometry
Crystalline Species	X-Ray Powder Diffraction
Anionic Species	Infrared Spectrophotometry
Hydroxide	Acid-Base Titration
Carbonate	Non-Dispersive Infrared Spectrometry
Sulfate	Ion Chromatography
Sulfite	Iodine Titration
Chloride	Ion Chromatography
Chemical Composition of Extracts	
Elemental Composition	Inductively Coupled Argon Plasma Emission Spectrometry and Atomic Absorption Spectrophotometry
Water Quality Parameters	pH meter, Conductivity Meter, Gravimetric Analysis
Total Sulfur as Sulfate	Ion Chromatography
Fluoride	Ion Selective Electrode
Chloride	Mercurimetric Titration
Other Tests	
Moisture	Gravimetry and Thermogravimetric Analysis
Insoluble Material	Gravimetric Analysis
Strength Development	ASTM Method D-1633
Permeability	Falling Head Permeameter and Constant Head Permeameter
Radioactivity	Gamma Ray Spectrometry, -Particle Counting and Radiochemical Separation
Extractions	EP Procedure as Described in May 19, 1980, Federal Register and Identical Extraction without Acetic Acid Addition

Source: Reference 3.

acceptable compressive strengths were generally in the range of 20 to 25 pounds of water per 100 pounds of dry waste product.

Permeability coefficients ranged from 10^{-4} to 10^{-10} cm/sec with most values between 10^{-5} and 10^{-6} cm/sec. These values agree with other reported values for dry FGD wastes and are similar to literature values for untreated wet scrubber sludges.

Measured elemental concentrations in waste solids from the Joy/Niro Riverside demonstration unit and Mikropul/Koch Strathmore system are shown in Tables 5-5 and 5-6 respectively. These results are presented as examples of elemental concentrations measured during the study. Solids from the Riverside unit represent a full-scale spray dryer on a utility boiler burning coal from Montana. The sample was collected at the fabric filter and solids from the spray dryer hopper were being recycled. The solids from Strathmore represent a spray dryer on an industrial-sized boiler where no recycle was employed. Both spray dryers use lime as the reagent. Differences in the waste solids composition can be attributed to differences in fly ash composition and differences in relative amounts of fly ash, unreacted reagent, and desulfurization products.

According to the leachate composition measurements, all of the waste products tested would be classified as non-toxic under May 19, 1980, RCRA rules and regulations. Batch extractions showed, however, that primary maximum contaminant levels (MCL's) for drinking water supplied were exceeded for four trace elements in several neutral extracts. Results of the batch extractions are shown graphically in Figure 5-1. Several samples exceeded the MCL for barium before curing, but all barium levels were below the MCL after curing. Most extracts were below the MCL for chromium after curing. Concentrations of arsenic and selenium exceeded MCL's only for products from sodium-based systems. Extracts from cured sodium-based products were lower but still exceeded MCL's for arsenic and selenium.

(d) Radian Corporation is also conducting waste disposal studies for DOE's Grand Forks Energy Technology Center (GFETC)(4). The overall goal of the study is to evaluate disposal requirements for solid waste from power stations burning low-rank western coals. The study will be conducted in three parts involving (1) sodium-based dry FGD products, (2) fluidized-bed combustion by-products, and (3) fly ash scrubbing FGD sludges. The first part of the study has been completed, and studies on fluidized bed combustion by-products are now underway.

In the GFETC study, physical and chemical tests were carried out on five dry FGD waste samples. One sample was from a spray dryer using sodium bicarbonate, and four samples were from dry injection

TABLE 5-5. ELEMENTAL ANALYSIS[a] OF SPRAY DRYER PRODUCT FROM BAGHOUSE DURING RECYCLE DEMONSTRATION RUN IN JOY/NIRO TEST FACILITY AT RIVERSIDE STATION

	SOLID SAMPLE[b]		NEUTRAL EXTRACT[c]			EP EXTRACT[d]				
			Uncured[b]		Cured	Uncured[b]		Cured	MCL for Drinking Water[e]	Detection Limit
Element	(μg/g)	(μg/g)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Aluminum	58,000	58,000	1.8	1.1	1.5	1.3	2.3	<0.05	-	0.05
Antimony[f]	<8	<8	<0.2	<0.2	<0.03	<0.2	<0.2	<0.03	-	0.03
Arsenic[f]	30	28	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	0.05(P)	0.003
Barium	350	820	0.96	1.0	0.39	0.93	1.5	0.47	1. (P)	0.0006
Beryllium	4.3	4.0	<0.003	<0.003	<0.0005	<0.003	<0.003	<0.0005	-	0.0005
Boron	ND[g]	ND[g]	1.9	1.7	0.76	1.4	1.6	0.82	-	0.009
Cadmium[f]	<1.0	<1.0	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	0.010(P)	0.0005
Calcium	150,000	150,000	360	360	88	2,300	2,400	110	-	0.04
Chromium	52	39	0.31	0.24	0.06	<0.005	0.099	0.011	0.05(P)	0.001
Cobalt	4.9	4.8	<0.03	<0.03	<0.006	<0.03	<0.03	<0.006	-	0.006
Copper	16	33	0.19	0.066	<0.001	0.019	0.086	<0.001	1(S)	0.001
Iron	20,000	21,000	0.082	0.064	0.014	0.084	0.089	0.019	0.3(S)	0.007
Lead[f]	<20	<20	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.05(P)	0.003
Magnesium	15,000	15,000	0.62	0.33	0.56	230	240	3.2	-	0.03
Manganese	630	630	0.015	0.009	0.009	4.1	4.6	0.09	0.05(S)	0.001
Mercury[f]	ND[g]	ND[g]	0.0004	0.001	<0.0002	0.0017	0.0004	0.0003	0.002(P)	0.0002
Molybdenum	16	16	0.53	0.49	0.072	0.52	0.55	0.056	-	0.002
Nickel	215	220	0.05	0.031	<0.003	0.1	0.18	0.006	-	0.003
Potassium	4,300	4,600	7.9	9.7	1.0	9.5	8.9	2.3	-	0.04
Selenium[f]	<20	<20	<0.004	<0.003	<0.003	0.01	0.012	<0.003	0.01(P)	0.004
Silver	<0.5	<0.5	<0.01	<0.01	<0.002	<0.01	<0.01	<0.002	0.05(P)	0.002
Sodium	2,700	2,600	15	14	11	17	19	10	-	0.005
Strontium	1,900	1,960	12	12	1.3	16	17	1.5	-	0.001
Thallium	<25	<25	<0.4	<0.4	<0.09	<0.4	<0.45	<0.09	-	0.09
Tin	<36	<30	<0.6	<0.6	<0.1	<0.6	<0.6	<0.1	-	0.12
Titanium	3,100	3,200	0.03	<0.03	<0.005	<0.02	<0.025	<0.005	-	0.005
Vanadium	580	610	0.47	0.35	0.2	0.7	0.82	0.12	-	0.003
Zinc	37	23	0.022	<0.02	<0.003	<0.02	<0.02	<0.003	5(S)	0.003

[a] Concentrations measured using inductively coupled argon plasma emission spectrometry unless otherwise noted.

[b] Duplicate digestion and analyses were carried out on solid samples; duplicate extractions and analyses were carried out on uncured samples.

[c] Neutral extract obtained using EP extraction procedure, but without acetic acid addition.

[d] EP Extraction Procedure described in Federal Register 45 (98) 33127, May 19, 1980.

[e] Maximum Contaminant Levels for public drinking water supplies: Primary (P), Federal Register 40 (24), December 24, 1975; Secondary (S), Federal Register 42 (62), March 31, 1977.

[f] Measured by atomic absorption spectrophotometry.

[g] Not determined because boron and mercury are lost during digestion procedure.

Source: Reference 3.

TABLE 5-6. ELEMENTAL ANALYSIS OF SPRAY DRYER PRODUCT FROM BAGHOUSE AND SPRAY DRYER HOPPERS (MIXED) WHEN PEBBLE LIME WAS USED AS REAGENT IN MIKROPUL'S FLUE GAS DESULFURIZATION SYSTEM AT STRATHMORE PAPER COMPANY

	SOLID SAMPLE	NEUTRAL EXTRACT[a]		EP EXTRACT[b]			
		Uncured	Cured	Uncured	Cured	MCL for Drinking Water[c]	Detection Limit
Element	(µg/g)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Aluminum	18,000	0.65	1.1	0.75	<0.05	-	0.05
Antimony	<8[d]	<0.2	<0.03	<0.2	0.051	-	0.03
Arsenic	38[e]	0.005[e]	<0.003	0.005	0.024	0.05(P)	0.003
Barium	100	1.1	0.18	1.1	0.44	1. (P)	0.0006
Beryllium	12	<0.003	<0.0005	<0.003	<0.0005	-	0.0005
Boron	ND[f]	1.7	0.45	1.5	0.56	-	0.009
Cadmium	<1.0	0.021[e]	<0.0005	<0.01	<0.0005	0.010(P)	0.0005
Calcium	220,000	1,020	95	2,800	1,200	-	0.04
Chromium	33	0.061	0.006	<0.005	<0.001	0.05(P)	0.001
Cobalt	14	<0.03	<0.006	<0.03	<0.006	-	0.006
Copper	15	0.086	0.012	<0.005	<0.001	1(S)	0.001
Iron	34,000	0.05	0.015	0.18	0.15	0.3(S)	0.007
Lead	<20	0.003[e]	<0.002	0.003[e]	<0.002	0.05(P)	0.003
Magnesium	3,100	0.27	0.086	1.0	2.7	-	0.03
Manganese	71	0.009[e]	0.002	<0.006	0.027	0.05(S)	0.001
Mercury	ND[f]	0.0004[e]	0.0003	0.0017	<0.0002	0.002(P)	0.0002
Molybdenum	3.6	0.15	0.029	0.05	0.009	-	0.002
Nickel	43	0.02	<0.003	<0.02	<0.003	-	0.003
Potassium	2,500	9.1	124	8.1	125	-	0.04
Selenium	<20	0.005[e]	<0.003	0.005[e]	0.005	0.01(P)	0.004
Silver	<0.5	<0.01	<0.002	<0.002	<0.002	0.05(P)	0.002
Sodium	710	4.2	8.7	3.1	6.9	-	0.005
Strontium	300	3.6	1.1	4.0	2.5	-	0.001
Thallium	<25	<0.4	<0.091	<0.4	<0.091	-	0.09
Tin	<30	<0.6	0.19	<0.6	0.13	-	0.12
Titanium	1,050	<0.02	0.013	<0.02	<0.005	-	0.005
Vanadium	52	0.077[e]	0.015	<0.02	<0.003	-	0.003
Zinc	69	0.016[e]	<0.003	<0.02	<0.003	5(S)	0.003

---

[a] Neutral extract obtained using EP extraction procedure, but without acetic acid.

[b] EP extraction procedure described in Federal Register 45 (98) 33127, May 19, 1980.

[c] Maximum Contaminant Levels for public drinking water supplies: Primary (P), Federal Register 40 (24), December 24, 1975; Secondary (S), Federal Register 42 (62), March 31, 1977.

[d] "Less than" values indicate analytical detection limit.

[e] Concentration measured is less than five times analytical detection limit.

[f] Not determined because boron and mercury are lost during digestion procedure.

Source: Reference 3.

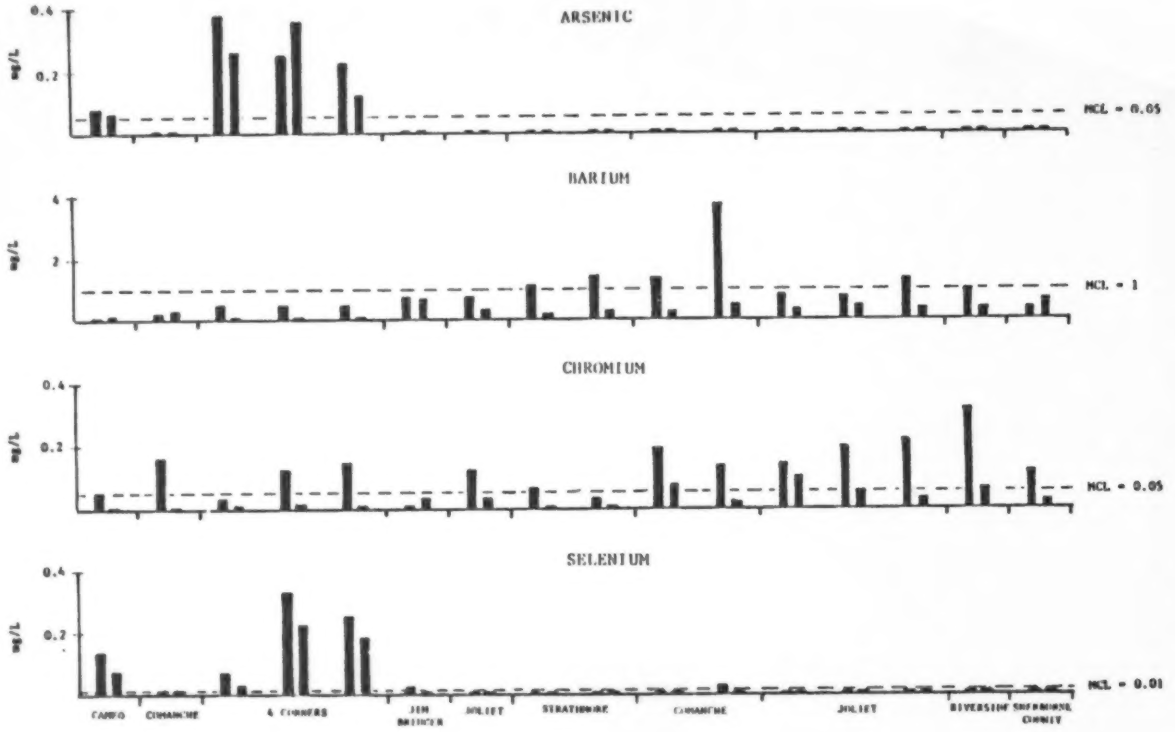


Figure 5-1. Concentrations of arsenic, barium, chromium, and selenium in neutral extracts of dry scrubbing waste products before and after curing. Concentrations in extracts of cured samples are shown to the right of concentrations in samples as discharged.

Source: Reference 3.

pilot-scale systems using trona and nahcolite. Physical and chemical properties measured included water solubility, solids moisture content, density, surface area, size distribution, and permeability. The chemical composition of the solids and leachate from the solids was also determined.

The results of solubility tests showed that sodium-based dry FGD waste is very soluble in water. In the batch dissolution tests employed, nearly half of each sample dissolved. In comparison, solubilities of sludges from calcium-based systems are typically near 4 percent.

Leachate tests showed that a substantial fraction of arsenic, molybdenum, selenium, sodium, and vanadium present in the solids will dissolve under dynamic leaching conditions. Up to 20 percent of the arsenic present and 40 percent of the selenium present were leached under the conditions used. Leachate generated by water coming in contact with wastes can be expected to contain high concentrations of dissolved salts and of some trace elements. Leachate of this quality can contaminate high quality surface water or ground water resources if released to them at significant rates (i.e., without controls).

Current practices for disposal of sodium-based dry FGD wastes include (1) dry ponding in very arid environments, (2) disposal in worked out areas of a mine site, and (3) disposal in ponds lined with 15 ft of clay. The success and costs of these practices depend strongly on favorable site-specific conditions. Due to the poor quality of leachates from untreated sodium-based dry FGD wastes, widespread use of sodium-based systems may require the development of more generally applicable disposal practices.

5.2 CURRENT AND PLANNED DISPOSAL METHODS FOR COMMERCIAL UNITS

The studies performed by most dry FGD system vendors to date have not indicated that any special treatment is required for disposal of dry FGD wastes. Consequently, the current and planned disposal methods for dry FGD commercial systems are not much different from the established disposal methods for wet FGD systems. Waste from both the Strathmore Paper Company system at Woronco, Massachusetts and the Celanese Fibers Company system at Cumberland, Maryland, is being trucked to landfills. Wastes from the Argonne National Labs system is being landfilled on-site. Waste disposal methods for the Container Corporation system in Philadelphia have not been reported.

Tentative waste disposal plans by utilities with contacts for commercial systems range from dry landfill to ponding of wetted solids. Ten of the 11 utilities that have or will have spray drying systems have reported disposal plans as follows:

- 2 natural clay-lined landfills
- 1 PVC-lined landfill
- 1 wetted transport to landfill
- 1 landfill with fixation
- 1 clay-lined ponding of wetted solids
- 2 dry landfills
- 2 unspecified landfills.

Of the two FGD system demonstration units in operation, one is trucking wastes to a landfill (Riverside) and the other will likely landfill waste solids at the mine site (Jim Bridger).

5.3 REFERENCES

1. Stevens, N. J., et al. Dry SO_2 Scrubbing Test Program. Draft Report. EPA Contract No. 68-02-3190. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. May, 1981.

2. Donnelly, J. R., et al. "Dry Flue Gas Desulfurization End-Product Disposal Riverside Demonstration Experience." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20.)

3. Thompson, C. M. and R. G. Rhudy. "Characteristics of Waste Products from Dry Scrubbing Systems." (Presented at the 1982 EPA/EPRI FGD Symposium, Hollywood, Florida, May 17-20.)

4. Thompson, C. M. and R. F. Jones. Chemical and Physical Characterization of Western Low-Rank Coal Waste Materials Part 1: By-Products From Sodium-Based Dry Scrubbing Systems. Draft Final Report, February, 1982. Prepared for U. S. Department of Energy, Contract No. DE-AC18-80FC10200.

APPENDIX A

CONVERSION FACTORS

To Convert From English	To SI	Multiply By
cfm	m^3/hr	1.70
ft	m	0.305
gr/scf	kg/m^3	0.00229
in.	m	0.0254
in. H_2O	Pa	249
lb	kg	0.454
gal	m^3	3.79
gal/1000 ft^3	liters/m^3	0.13
BTU	joule	0.252
short ton	tonne	0.91

The temperature conversion formula between English and SI units is:

$$\frac{{}^{o}F - 32}{9} = \frac{{}^{o}C}{5} \qquad \text{(A-1)}$$

where: ^{o}F = degrees Fahrenheit

^{o}C = degrees Celsius